UNIVERSITY OF ALBERTA

Environmental and Equity Objectives in Traffic Assignment Modelling

By

Marie Christine Benedek ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

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To
My Parents
who have provided support and inspiration

Abstract

There have been two recent changes in the transportation field that may have an effect on traffic assignment techniques. The first is the increasing concern by the general public on the amount of air and noise pollution generated by transportation activities. The second is the advent of Intelligent Transportation Systems (ITS) in which in-vehicle route guidance systems or electronic toll collection technologies allow transportation engineers to directly affect driver routing strategies and hence decrease congestion and pollution on urban networks.

This new combination of the ITS technologies and environmental policies introduces new objectives in traffic assignment modelling. This thesis examines the implications of traffic assignment where the objective of reducing air pollution is achieved by directly or indirectly routing the vehicles by ITS. Furthermore, the thesis examines the potential for routing traffic to achieve a system equitable objective where the traffic is routed on the network to ensure that the pollution levels are the same for all the residents living within the network. The analysis of environmental and equity objectives in traffic assignment modelling is first tested on several small networks and subsequently tested on larger realistic urban networks.

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Chapter 1 - Introduction

1.0 Overview

The increased concern of the general public towards the reduction in vehicular pollutants requires transportation engineers to rethink current transportation objectives and policies. One of the most common objectives in transportation planning is to reduce urban traffic congestion and negative byproducts such as noise or vehicular pollutants. Historically, this goal was achieved by increasing roadway capacities through building new roadways. Similarly, the primary means of reducing noise or vehicular pollution was through legislation and design of newer, quieter and cleaner automobiles. Presently, constructing roads has become costly and therefore new attempts towards reducing traffic congestion are under way with Intelligent Transportation Systems (ITS) technologies such as in-vehicle route guidance systems or electronic toll collection systems. The reduction of air pollution from traffic routing strategies will be technologically possible with future ITS. This thesis examines the potential to influence some of the environmental objectives by non-traditional routing strategies and principles. Both small, hypothetical networks and large, realistic networks are used as a basis for this investigation.

It is important for traffic engineers to model the environmental effects on an urban network because implementing pilot studies to examine the wide range of different scenarios would be too costly or impossible. Computer models are also an effective way of predicting future traffic conditions and air pollution levels. To date, little work has been done on modelling traffic routing problems based on environmental objectives because there was no means of implementing such traffic routing strategies on a realistic network. However, with the advent of ITS technologies, routing traffic based on environmental objectives will become feasible and the need to model such conditions is apparent.

1.1 Intelligent Transportation Systems

In the last five years Intelligent Transportation Systems (ITS) such as route guidance systems and electronic toll collection systems have been used as potential traffic management schemes for the purpose of reducing congestion. It is acknowledged that there are a wide variety of benefits with reducing congestion. For example, air pollution and wasted fuel consumption may be reduced in less congested traffic conditions. ITS technologies may influence driver behaviour in several different ways which can be divided into the following categories: Advanced Traffic Management Systems (ATMS), Advanced Traveller Information Systems (ATIS), Commercial Vehicle Operations and Advanced Vehicle Control Systems (Euler, 1990).

ATMS may influence driver behaviour by responding to changes in traffic flow through area wide surveillance and real time information. One of the main functions of ATMS is to aid in providing quick response to traffic incidents. It is also possible through ATMS to implement the use of electronic tolls along major corridors. Electronic toll collection technologies are described later in the next section.

Advanced Traveller Information Systems (ATIS) provides real time information to the drivers on congestion and alternate routes through in-vehicle route guidance navigation systems or cable television. In-vehicle navigation systems guide the driver along a route from either a distributed or centralized traffic control centre (Rilett, 1992). Both the distributed and centralized route guidance systems are considered an active measure where the driver is told which route to take based on real time information collected by detectors along the roadway. A distributed route guidance system is user-oriented because real-time information from a centralized computer station is sent to an on-board computer within the vehicle. The on-board computer calculates the optimal route based on the broadcasted information and user objectives. A centralized route guidance system is described as being more system-oriented because explicit routes are calculated for all the guided vehicles by a central computer and transmitted to the individual vehicles.

ITS technologies may influence commercial vehicle operations by including automatic processing of truck regulations or the use of weigh-in motion scales. ITS can also be used for scheduling bus or paratransit operations. Finally, the Advanced Vehicle Control Systems category may influence driver behaviour through aiding the drivers in their driving tasks. This may therefore increase roadway capacities and reduce traffic accidents.

The focus of the thesis is based on the first two categories of ITS technologies: ATMS and ATIS. For example, ATMS may influence driver route choice through electronic tolls and ATIS may involve the routing of traffic such that the individual or system environmental costs are minimized.

One of the features of ITS that has progressed significantly in the last five years is the use of electronic toll collection systems. Electronic tolls influence driver route choice because the drivers are charged an amount based on driving conditions and time of day. This form of ITS influences driver behaviour in a more indirect sense because route selection is not actually calculated by a computer and the final route choice is by the driver.

In the last forty years, road pricing has been used in the United States to maintain the current levels of service on freeways and interstates. In Canada, road pricing has been implemented in Quebec and Nova Scotia on major bridge passages in Montreal and Halifax. Today, all levels of government are providing less money for transportation infrastructure. In the future, it is likely that transportation agencies will rely more heavily on road pricing schemes to provide funds for maintaining and building roadways and provide a means of mitigating congestion.

The use of electronic tolls are more efficient than standard toll booths along a corridor. For example, the drivers do not have to stop in order to pay the fee. Electronic tolls can also be used to vary the road pricing along a corridor for different time of day, location, vehicle occupancy, type of vehicle and may possibly be used to charge the vehicle based on the amount of pollutants emitted by the vehicle in a given area.

Some electronic toll collection systems require some kind of automated vehicle identification method (AVI) in order to track a moving vehicle. The AVI system tracks the vehicle by recording the license plate along the route of travel (Levine et al. 1994). Furthermore, AVI systems not only provide a mechanism for toll collection but they can also measure link travel times automatically at many locations or determine speed changes over a corridor. Other possible more feasible electronic toll collection systems are prepaid “smart cards” displayed on the vehicle. The prepaid amount is decreased every time the vehicles passes a location along the corridor.

1.2 Environmental and Equity Objectives

Transportation engineers must therefore determine how environmental objectives may be modelled with ITS technologies and the present transportation models. In effect transportation engineers need to determine new objectives and new means of meeting these objectives. Traditional traffic assignment techniques usually model route flows based on minimizing a generalized cost function from a user equilibrium or system optimal perspective. A user equilibrium assignment may be defined as the assignment of traffic on a network such that the generalized cost function on all used routes for a particular origin-destination pair is equal and all unused paths have higher generalized costs (Wardrop, 1952). Contrary to this UE principle, the system optimal assignment principle is defined as the routing of traffic on a network such that the total generalized cost function is minimized.

Most traffic assignment models assume that drivers attempt to minimize their own travel time or generalized costs that includes a number of other factors such as out-of-pocket costs, number of stops, and environmental factors. The concept of the generalized cost is explained in greater detail in Chapter 2.

In the last twenty years, models regarding fuel consumption, pollutant emissions and noise pollution have been developed by researchers and transportation engineers. However, the effects of vehicular emissions on urban networks when different routing objectives such minimizing the total CO emission have not been extensively examined. Because the traffic assignment techniques are based on a generalized cost function, the traffic assignment could include generalized cost functions based on the environment. The only changes required would be to determine the appropriate cost functions to model traffic routing strategies based on environmental objectives. However, identifying the appropriate cost functions is problematic because little research has been done towards determining functions suitable for traffic assignment problems.

Furthermore, the increased concern on the local effects of pollution levels due to the system operators' actions such as roadway closures (e.g. the closure of Keillor Road in Edmonton) or the implementation of toll roads may generate routing options within the system that are based on equity measures. For example, system operators may be able to route traffic such that the effects of pollution caused by the traffic is equal for all the people living in neighbourhoods that are nearby major arterials. Furthermore, traffic could also be routed on the network to achieve air pollution levels that do not exceed some maximum standard (Rilett et al., 1993).

1.3 Objectives of the Thesis

The basic goal of the research has been to investigate the impact on pollutant emissions on an urban network when non-traditional objectives such as minimizing CO emissions are included in a traffic assignment model. This goal is accomplished by addressing several important questions which involve determining the effect on route flows and overall system costs when the objective is to route traffic based on minimizing vehicular pollutants from a user equilibrium, system optimal or system equitable perspective. It is assumed that traffic routing based on environmental objectives will be made possible by ITS technologies. For example, real time information on vehicular emissions could be provided by automated vehicle tracking devices. This information could be transmitted to a central computer which could then adjust the routes to minimize vehicular emissions. Furthermore, the effect of tolls on the routing of traffic to minimize vehicle pollutants will also be addressed in the thesis.

Moreover, it is also important to identify the appropriate cost functions to model routing strategies based on environmental objectives. In this thesis, vehicular pollutant emissions and fuel consumption cost functions have been adopted from the literature.

The underlying reason for examining the subject of "environmental routing" is due to the need increase awareness towards the modelling of environmental objectives with the present traffic assignment techniques. Specific questions addressed in the thesis include:

1. What is the impact on the user or the system when environmental objectives are introduced into the generalized cost function of a traffic assignment model for a realistic network? (Chapter 4)

2. What happens to the link flows, overall system travel time, fuel consumption and pollutant emissions on an urban network when an equitable assignment model is implemented? (Chapter 5)
3. It is possible to accurately model the principle of equity with the traffic assignment techniques presently available? (Chapter 5)
4. If toll charges are introduced on a network, what is the effect on link flows and the impact on the air pollution of the adjacent streets of the tolled roadway? Secondly, how can toll charges be modelled in a traffic assignment model? (Chapter 6)

1.4 Approach to the Problem

The ASSIGN traffic assignment model developed at the University of Alberta by Dr. L.R. Rilett (Rilett, 1992) is the primary tool used in this thesis to model non-conventional objectives in traffic assignment problems. The ASSIGN model is used because commercial traffic assignment models such as CONTRAM do not have the program code available to make modifications to the objectives of the traffic assignment problem. The ASSIGN program code is available and it is therefore possible to make adjustments to the generalized cost functions and program objectives.

The differences in traffic routing principles based on environmental conditions are illustrated with several sample networks and then analyzed on realistic networks which represent the University area of the City of Edmonton and the City of Ottawa, Ontario. Most of the results of the research are related to the University network where the effects on pollutant emissions at an aggregate level and disaggregate level are analyzed for the a.m. peak hour where the origin-destination (O-D) demand are fixed and represent the year 1993. The Ottawa network is used only in Chapter 4 in order to determine whether the trends found in the University network are the similar as those for an even larger network that is composed of higher arterial speeds. It is also used as part of the validation of the results found when the traffic is routed by environmental objectives.

1.5 Scope of the Thesis

The research in this thesis pertains to modelling the assignment of automobiles to a network under different objectives and considering additional costs other than travel time. Research into this area has been limited and consequently a number of assumptions were made in order to allow the research to proceed in a timely manner. None of the assumptions may be considered to limit the techniques developed or the general results found. In addition, the assumptions are not significantly different from what is currently used in traffic assignment practice.

The additional costs examined in this thesis are noise, fuel consumption, CO emissions, and HC emissions. It is important to note that while other environmental costs, such as carbon dioxide, sulphuric acid, and particulate matter were not considered, they may be readily examined using the techniques developed in the following chapters.

As discussed in the coming sections, a macroscopic, traffic assignment model was used as a test bed for the research. Consequently, the total origin-destination demand and mode of travel is assumed fixed. However, the techniques developed are general and these restrictions may be relaxed in the future.

The general outline of each chapter is essentially the same. The assignment theory is discussed and the associated assignment technique is first demonstrated on a small test network. Subsequently, a larger network is analyzed in order to examine the trends on a more realistic network. A network from Edmonton was chosen as the primary traffic network, although one from Ottawa was also used. The effect of the different routing objectives on the overall travel time and pollutant levels was examined at an aggregate and disaggregate level. The pollutants examined were based on tailpipe emissions and the effects of dispersions of the pollutants were not examined. An analysis of societal costs, both at a local and global level, were beyond the scope of the thesis. However, the work does provide a means of quantifying the magnitude of these costs such that a societal impact analysis may easily be undertaken.

1.6 Overview of the Thesis

The thesis consists of seven chapters. Chapter 2 is a literature review of the main topics related to traffic assignment modelling and environmental objectives. The review consists of a summary of the well-known traffic assignment techniques and an overview of vehicle pollutants and how they are presently modelled.

Chapter 3 introduces Edmonton's University network which is used throughout the thesis and describes the validation of the ASSIGN model. The link flows generated in the ASSIGN model are directly compared with the CONTRAM model and actual data counts obtained from the City of Edmonton.

Chapter 4 is an overview of modelling traffic assignment problems from an environmental point of view. In this chapter the concepts are introduced by illustrating results for a sample 2 link network. Then, the traffic assignment model is used to model the effects on link flow, link travel time, fuel consumption, CO emissions and HC emissions for a larger network -- the University network introduced in Chapter 3.

In Chapter 5, the environmental objectives in the traffic assignment model are based on a new type of traffic assignment principle -- a system equitable assignment (SE). In this chapter, the shortcomings of the conventional traffic assignment techniques are discussed for a system equitable assignment. The advantages of an incremental assignment to model a network from a system equitable principle is introduced for a simple two link network and then further analyzed in the University network.

In Chapter 6, the introduction of toll charges on a network is discussed. The concept of including a toll which is related to the user's value of time is first analyzed for a small network whereby the advantages of randomizing the value of time are presented. The second section of Chapter 6 illustrates the changes in the environmental objectives introduced in Chapter 4 when a Keillor Road on the University network is subjected to a toll charge.

Lastly, in Chapter 7, the conclusions and recommendations arising from this thesis are presented.

Chapter 2 - Literature Review

2.0 Introduction

There has been an increased concern in the last ten years by the general public and transportation engineers over the amount of pollutants emitted into the environment from transportation activities. This has lead to an interest in new techniques in traffic assignment modelling where objectives such as minimizing noise pollution, vehicle emissions or fuel consumption may be implemented into transportation planning and modelling activities. To date, researchers have established several different ways of modelling noise and air pollution. However, little research has been done on analyzing the effects of traffic routing based on environmental objectives on a realistic network. The focus of this chapter is to introduce the concepts in traffic assignment and to summarize the work already done in air and noise pollution modelling.

The first three sections of this chapter describe the well known traffic assignment techniques which may generally be categorized into two methods: Non-Equilibrium, and Equilibrium methods (Matsoukis, 1986). An overview of the general concepts of traffic assignment techniques is first presented. Second, the non-equilibrium methods are described. Third, the equilibrium methods that are used to find an optimal solution for the user equilibrium and system optimal assignment models are summarized.

Also included in the literature review is an overview on air and noise pollution models. The reason for examining this is twofold. First, it is important to identify the appropriate generalized cost functions to model fuel consumption, pollutant emissions and noise pollution in traffic assignment. Second, the cost functions introduced in this chapter will be implemented into the new traffic assignment models developed in this thesis.

2.1 Traffic Assignment Techniques

Traffic assignment techniques are used to determine the origin-destination (O-D) route flows on a network given the link characteristics and the (O-D) demand rate. It is usually assumed that drivers choose their routes to minimize their own travel time (or in a more general term, their own generalized cost) and therefore the network is modelled in some form of equilibrium. The concept of equilibrium models in traffic assignment modelling were first introduced by Wardrop (1952). His first principle, known as the user equilibrium traffic assignment model, states that traffic is routed on the network such that the generalized cost on all used routes for the same origin-destination pair is equal and all unused routes have equal or greater costs.

However, with ITS technologies, the user equilibrium assignment can be influenced indirectly by the use of electronic tolls. For example, toll charges would be set by system operators whereby they would vary the toll depending on the time of day or set a toll depending on the amount of pollutants emitted in an area.

Traffic engineers have also examined traffic assignment problems from a system optimal point of view where traffic is routed explicitly with the objective that the total system travel time or generalized cost function is minimized (i.e. Wardrop's second principle). The system optimal assignment technique may not be very practical from the user viewpoint because it is unlikely that drivers would be willing to increase their own travel time or generalized cost to generate system benefits. Therefore, a system optimal assignment is performed to obtain some kind of reference point.

In an ITS environment, system operators may influence driver route choice directly by a centralized route guidance system whereby explicit routes are given to the user through an in-vehicle route guidance navigation system. A mathematical translation of the user equilibrium and system optimal traffic assignment principles are described in section 2.3.

The generalized cost function in a traffic assignment model can include a number of other factors other than travel time such as out-of -pocket costs and travel distance. However, with the rapid advancement of ITS technologies, the objectives of the user or the system and the assumptions to the standard traffic assignment models need to be re-examined. Because traffic assignment programs are based on a generalized cost function, the effects of vehicular pollutants or noise pollution on the general public and on the changes in route flows could be also included into the traffic assignment model. The only changes required would be to determine the appropriate cost functions and use the traditional traffic assignment techniques to analyze route selection based on environmental conditions. Generalized cost functions that include out-of-pocket costs such as toll charges have also been examined by researchers (Leurent, 1994). In later sections, generalized cost functions that include out-of-pockets cost and environmental costs will be introduced.

The next two sections describe different types of traffic assignment techniques used by traffic engineers and researchers mentioned in section 2. First, the non-equilibrium traffic assignment techniques are discussed. This is then followed by a mathematical definition of the user equilibrium and system optimal assignment models.

2.2 Non Equilibrium Traffic Assignment Techniques

The following section is an overview of traffic assignment techniques known as the non-equilibrium assignment methods. The non-equilibrium methods attempt to assign vehicles to a minimum cost path by using non-convergent algorithms to reach equilibrium. These methods were first introduced in the 1960's. They were used in an attempt to reach convergence by non-equilibrium conventions because the linear programming techniques that guaranteed convergence in traffic assignment modelling were not yet developed. The non-equilibrium methods include: All-or-Nothing assignment (AON), capacity restraint assignment, and logit and probit loading models.

2.2.1 All-or-Nothing Assignment (AON)

The All-or-Nothing assignment procedure was one of the first methods used by traffic engineers for predicting link flows on large networks. This process involves assigning the total O-D demand to a minimum cost path. This minimum cost path is usually identified by a shortest path algorithm (Rilett, 1992) such as the label setting or the label correcting algorithm.

However, the AON assignment tends to produce unrealistic link flows because certain links will receive most of the traffic flow while others will receive very little. It should also be noted that when the flow is added on the network, the route may not actually be the minimum because the capacity of the links in the network is not considered.

The only factor usually considered is the free flow link travel time which is assumed to remain constant as the flow on the link increases.

An AON assignment is usually not used exclusively. This technique is normally combined with other models. For example, an AON assignment is used as part of the solution in the convex combinations algorithm for the equilibrium traffic assignment technique as will be shown in section 2.3.3

2.2.2 Capacity Restraint Assignment

The capacity restraint assignment is an improvement to the AON assignment because the capacity of the links is considered and thus the travel time varies as the link flows increase. A travel time function shown in Equation 2.1 was developed by the Bureau of Public Roads (U.S.D.O.C., 1964). It has been widely used to determine individual link travel times and it is commonly known as the BPR function.

$$t_a = t_o(1+\alpha_a(\frac{v_a}{c_a})^{\beta_a}) \tag{2.1}$$

Where:

t_a = link travel time
t_0 = free flow link travel time
v_a = link flow
c_a = capacity of the link
α_a, β_a = BPR constants

The capacity restraint assignment method can be further categorized into an iterative assignment and an incremental assignment. The iterative assignment technique loads link flows onto the network by adjusting the travel time function at each iteration (U.S.D.O.C, 1964). It is a capacity restraint model because the link travel times are directly affected by the increase in link flow and successive link flows for each origin-destination pair at each iteration are influenced by the increase in link travel time. The technique is summarized by the following steps:

1. An initial AON assignment is performed to determine the flows on the links in the network. This AON assignment is based on the free flow link travel times (t_a^0).
2. The travel times are updated from the previous AON assignment.

3. A new minimum tree is found by using a temporary weighted mean travel time as defined in Equation 2.2. This is also known as the "smoothing" effect which prevents the algorithm from oscillating between two minimum cost path trees.

$$t_a^n = .75t_a^{n-1} + .25t_a^n \qquad (2.2)$$

where:

n = Iteration number

t_a = Travel time on link a

4. The total O-D demand is then assigned to the tree found in step 3.

5. Steps 2-4 are repeated until a certain stopping criteria is met which is normally n=N where n=1,2,3...N

6. Finally, the link flows for the network are averaged based on the volumes obtained for each assignment iteration.

The incremental assignment is another capacity restraint method which loads onto a shortest path, a fraction of the total demand for each origin destination pair. Martin and Manheim (1965) were the first to use the incremental traffic assignment procedure in an attempt to improve convergence. The principle of the incremental traffic assignment technique is summarized below:

1. The total traffic demand for each origin destination pair is divided into a number of increments. In some incremental methods, the origin-destination pair increments are selected at random.

2. For each increment, the travel times are updated and a new minimum path tree is found.

3. Then an AON assignment using the incremental O-D demands is assigned to the network based on the minimum path tree found in step 2.

4. For each iteration, the link flows are added to the previous iteration.

5. Steps 2 - 4 are repeated until a certain stopping criteria is met which is normally n=N where n=1,2,.. N.

Both the iterative and incremental algorithms are heuristic because they do not guarantee convergence to the optimum. A stopping rule is always applied instead of a convergence criterion because convergence cannot be proven. One other weakness in these algorithms is that there are no specific rule for choosing the number of iterations. More iterations generates a solution towards convergence.

2.2.3 Logit and Probit Loading Models

The logit and probit loading models are based on the utility theory. In traffic assignment, a utility value is assigned to each route for each O-D pair. The utility of a particular route can be described as a function of the attributes of that route and the user's characteristics. Normally, the user will choose the alternative with the highest utility.

For example, if $U=(U_1,.. U_k)$, is a vector of utilities that represents several alternatives, and a is a vector of variables which includes the driver characteristics and route attributes, the utility can be defined as the deterministic component $V_k(a)$ plus a random error term as shown in Equation 2.3. In traffic assignment models, the deterministic component of the utility function is normally the travel time function. It is assumed that the random error term for a logit model is an independent Gumbel variate (Domencich and Mc Fadden, 1975).

$$U_k(a) = V_k(a) + \xi_k(a) \qquad (2.3)$$

To choose a certain alternative, the probability of one alternate, $U_k(a)$ must be higher than the utility of another alternative, $U_l(a)$. This is shown in Equation 2.4.

$$P_k(a) = \Pr(U_k(a) \geq U_l(a)) \qquad (2.4)$$

Where:

$P_k(a)$ = the choice probability
$U_k(a)$ = the current utility
$U_l(a)$ = the alternative

In traffic assignment, the most common logit model algorithm is known as Dial's algorithm. Dial formulated a traffic assignment technique from a probabilistic concept and it is based on the following specifications (Dial, 1971):

1. All "reasonable" paths should have a non-zero probability of use while all unreasonable paths should have a zero probability of use.

2. All "reasonable" paths of equal travel costs should have equal probability.
3. When there are two or more "reasonable paths of unequal costs, the path with the least cost should have a higher probability of use.

In Dial's algorithm, a reasonable path is defined as an efficient path which does not go back towards the origin. That is, each successive node on the path is further from the origin or closer to the destination than the previous node. Dial's algorithm is an assignment where the driver can choose among different alternative routes departing from a node. One of the major problems with Dial's algorithm is that the model cannot distinguish between relative differences in route costs. For example, the probability of choosing a route with a 10 minute difference on a 20 minute trip is the same as the probability of choosing a route with a ten minute difference on a 3 hour trip.

The probit model is also based on the utility theory. In traffic assignment, the travel time is still considered to be the deterministic component of the utility function shown in Equation 2.3. However, in this model the random error term ξ of each utility is normally distributed. The model assumes that the perceived link travel time is normally distributed with a mean equal to the actual link travel time.

The calculation of the error term is not elementary and the choice probability is usually estimated by an analytical approximation or by the Monte Carlo simulation. The analytical approximations however, cannot be used if there exists a large number of alternatives since the computations become excessively complicated and the accuracy decreases as the number of alternatives increases.

2.3 Equilibrium Traffic Assignment Models

As already mentioned in section 2.1, it is assumed that traffic is routed to reach equilibrium which may be either from a user or system point of view. Convergence of equilibrium traffic assignment problems were first introduced in the 1970's where a mathematical translation of Wardrop's user equilibrium and system optimal principles were developed in the form of a non-linear program subject to a number of constraints. The following section describes the user and system optimal assignment models from a mathematical perspective.

2.3.1 Static User Equilibrium Traffic Assignment

The concept of user and system equilibrium traffic assignment, as mentioned in section 2.1, is based on Wardrop's two principles (Wardrop, 1952). Wardrop's first principle (i.e. user equilibrium assignment) involves minimizing the cost of travel on all used routes for each origin-destination pair such that no other routes have a lower generalized cost. The user equilibrium model may be written mathematically as shown in Equations 2.5 and 2.6. The objective function in Equation 2.5 does not have a direct economic meaning. However, it is a mathematical term that results in a feasible solution at the optimal point (Sheffi, 1985).

$$\min z(f) = \int C_a(x)\,dx \qquad (2.5)$$

Subject to:

$$f_a = \sum d_{ar} h_r \qquad (2.6a)$$

$$\sum_{r \in R_{ij}} h_r = T_{ij} \qquad (2.6b)$$

$$h_r \geq 0 \qquad (2.6c)$$

Where:

$C_a(f_a)$ = Flow cost function on link a
f_a = Flow on link a
h_r = Flow on route r
d_{ar} = 1 if link a belongs to route r, 0 otherwise
T_{ij} = Demand from origin i to destination j

The first constraint states that the flow on link a must be equal to the sum of the flow on all routes r that use link a. The second constraint states that the total flow on routes r must be equal to the origin destination demands. These two constraints define flow conservation. The final constraint is a non-negativity constraint which ensures that the flows on routes r are greater than zero. Note that it is not necessary to introduce capacity constraints into the non-linear program because the travel time for each user will be very high if the flow on the link exceeds capacity.

In a deterministic user equilibrium assignment, it is assumed that all drivers have perfect knowledge of the link travel times. Even though the generalized cost function $C_a(f_a)$ is dynamic with respect to flow, it does not change with respect to time. A common algorithm used to solve the deterministic user equilibrium assignment is the convex combination method (Frank-Wolfe algorithm) and it is explained later in section 2.3.3.

2.3.2 System Optimal Assignment

Wardrop's second principle (i.e. the system optimal assignment model), states that drivers are routed such that the total travel time or generalized cost on the network is minimized. The objective of the system optimal traffic assignment is shown in Equation 2.7.

$$\min \sum_{a} t_a(f_a) * f_a \tag{2.7}$$

The objective function above is subject to the same linear constraints as in the user equilibrium assignment. This objective function determines the link flow pattern in terms of the total travel time or generalized cost associated with it relative to the total travel time or generalized cost of each driver.

2.3.3 Solving a Non Linear Programming (NLP) Problem with a Linear Approximation - Frank-Wolfe Algorithm

The user equilibrium model shown in section 2.3.1 is a NLP problem with linear constraints. In order to solve this NLP, by the method described by the Frank-Wolfe algorithm, the function z(f) must be convex. Convexity of a one dimensional problem can be determined by several ways (Sheffi, 1985):

1. If any line between two points on the graph of z(f) lies entirely above the graph.
2. If a line tangent to the graph of z(f) lies entirely below the graph.
3. If the graph of z(f) has nonnegative curvature at every point.

For example, if $C_a(x)$ in Equation 2.5 is the BPR function, the link travel times increase monotonically with flow which leads to an objective function that is convex. The NLP program can therefore be approximated by a linear function described by a first order Taylor series expansion. Equation 2.8 illustrates the first order Taylor series expansion.

$z(y) = z(f^1) + \nabla z(f^1)*(y-f^1)$ (2.8)

Where:

f^1 = Vector of link flows
$\nabla z(f^1)$ = Gradient of f^1
y = Vector of link flows for a temporary solution. In traffic assignment y is usually an assignment where the total O-D demand is assigned to the boundary of one of the constraints.

The above general form of the linearized non-linear program is used in the well-known convex combinations algorithm to solve the traffic assignment problem. This is also known as the Frank-Wolfe algorithm because the concepts of the user and system optimal assignment described in section 2.3.1 and 2.3.2 are used in the solution algorithm. The Frank-Wolfe algorithm is used to find the best solution among the plane in n dimensions of all feasible solutions (LeBlanc et al., 1975). The following is a discussion of the steps in the Frank-Wolfe algorithm.

Step 1: The initial feasible solution is first found by an AON assignment based on the free flow link travel times as shown in Equation 2.9. The AON assignment can be used, since the objective is to assign the flow to the minimum cost path. In this case, there are no other routes that will provide a shorter travel time. To assign the flow, a minimum cost path must first be found for each O-D demand. The minimum cost path is identified by a minimum cost path algorithm such as the label correcting or label setting algorithm.

$f_a^1 = AON^1$ (2.9)

Where:

f_a^1 = Vector of link flows for the first iteration
AON^1 = Vector of link flows based on an All-or-Nothing assignment

Step 2: Equation 2.10 shows that the link travel times are then updated based on the new link flow estimates.

$t_a^{n+1} = t_a(f_a^1)$ (2.10)

Step 3: The objective function is linearized and a solution to the new linear program is an AON assignment based on the link travel times calculated in step 2. In this step, the vehicles are removed from the current solution and added to the new auxiliary routes as shown in Equation 2.11 where y^{n+1} represents auxiliary link flows. Once new routes have been identified the next step is to determine how many vehicles should be assigned to the routes. This is accomplished by finding a search direction.

$$y^{n+1} = AON^{n+1} \tag{2.11}$$

Step 4: In this step, a search direction d is identified by taking the difference between the flows on the auxiliary route y^{n+1} and f_a^n, the current link flow estimates. The search direction is a line connecting the current solution and the temporary new solution as shown in Equation 2.12.

$$d^{n+1} = y^{n+1} - f_a^n \tag{2.12}$$

Step 5: In this step, λ^{n+1} is calculated by minimizing the objective function along d. This is done by standard one dimensional search techniques such as the bisection or golden section technique. The parameter λ is always between 0 and 1 where 0 indicates no movement toward y and 1 indicates that the new solution is y. Values for λ greater than 1 or less than 0 would produce a solution outside the constraints.

Step 6: The link flows are then updated. The new solution (f_a^{n+1}) is based on the old estimate plus the product of λ and the search direction.

$$f_a^{n+1} = f_a^n + \lambda^{n+1} (d^{n+1}) \tag{2.13}$$

Step 7: The final step is to determine if convergence of the algorithm has been achieved. Convergence can be determined in several ways. Normally, convergence is achieved when the solution to the objective function does not change considerably. However, it has been recorded in literature that convergence is obtained after 4 to 5 iterations (Sheffi, 1985). Rather than specifying the maximum percentage allowed between two consecutive flow vectors, the program specifies the number of iterations. The algorithm is stopped when the counter n has reached its maximum value otherwise, the counter is incremented by 1 and the algorithm is repeated at step 2.

2.3.4 Method of Successive Averages

The deterministic user equilibrium assignment can be modified to include a random component to the drivers' perception of travel time (Sheffi, 1985). This is known as a stochastic user equilibrium assignment. In a stochastic model, the link travel times are modelled as a random variable where a normal or log normal distribution represents the drivers' perception of travel time along a particular link as shown in Equation 2.14. The link travel times have a known mean and variance and thus the travel time on the minimum cost path route which is the sum of the individual link travel times on the minimum cost path also has a mean and variance.

$$TT_l \sim N\ (tt_l, \sigma) \tag{2.14}$$

Where:

TT_l = Random variable representing the link travel time
tt_l = Deterministic link travel time
σ = Standard deviation of the link travel time

To solve for a stochastic assignment model, the method of successive averages algorithm is normally used. The method of successive averages is similar to the Frank-Wolfe algorithm described above, however, the search direction is determined by the iteration number. The algorithm is as follows:

1. The initial link travel times are determined which generates an initial set of link flows based on a stochastic network loading procedure.
2. The link travel times are updated as shown in Equation 2.15.

$$t_a^{n+1} = t_a(f_a^{1}) \tag{2.15}$$

3. A stochastic network loading procedure is performed based on the current link travel times. This generates an auxiliary set of link flows similar to the flow pattern found in the Frank-Wolfe algorithm.

$$y^{n+1} = AON^{n+1} \tag{2.16}$$

4. The new set of link flows is then found by the following search shown in Equation 2.17.

$$f_a^{n+1} = f_a^n + 1/n\ (y^{n+1} - f_a^n) \tag{2.17}$$

5. The final step is to determine if convergence is attained. If not, then the counter is incremented by 1 (n+1) and the algorithm is repeated at step 2.

2.4 Generalized Cost Function Based on a User's Value of Time

In section 2.1, the generalized cost concept was introduced. It was also mentioned that ITS technologies such as electronic tolls or in-vehicle route guidance systems could have an effect on driver route choice. Traffic engineers therefore need to examine how this may be incorporated into a traffic assignment model. This section summarizes the research towards the modelling of toll charges with particular emphasis on the work recently published by Leurent (1994) who developed an algorithm to model toll charges within an urban network. His research work will be later used in chapter 6 where a toll charge will be implemented on a network to determine its effect on driver route choice.

Research towards a cost versus time equilibrium model examines another approach to modelling a user's value of time in a traffic assignment model. The model includes a cost associated with a roadway and a random value of time (VOT) for different users. The random value of time incorporates the fundamental theory that the value of time is perceived differently among users (Leurent 1993, Dial 1994). Leurent showed in a simple two route example that there exists some differences between a standard cost vs. time model where the value of time is constant and modified cost vs. time model where the value of time is random . His generalized cost function takes the form shown in Equation 2.18.

$$GT = \mathrm{T}_{rs}^{m} + \frac{\mathrm{P}_{rs}^{m}}{v} \tag{2.18}$$

Where:

GT = Generalized travel time

T_{rs} = Travel time on the path m from origin r to destination s.

v = Randomized value of time

P_{rs}^{m} = Monetary cost on path m for O-D pair r-s.

The two route example represented a case where drivers had the option of using a tolled highway or a roadway without a toll charge. In his standard model, the value of time remained constant whereas in his modified cost versus time model, the value of time parameter followed a log normal distribution. This value of time was therefore representative of the income distribution of a populated urban network. His research found that the standard cost versus time model could not calculate an optimal level of fare to be charged or maximum revenue on a toll road whereas the modified cost model could. He also showed that by randomizing the VOT for each origin-destination pair, link flows are significantly different once the toll charge on one route was high. In his two route example, link flows generated from the standard model were essentially zero on the tolled highway for high toll charges. However, in the modified version, the some drivers continued to used the toll highway even at high toll charges.

2.5 Generalized Cost Functions Based on Environmental Conditions

As already mentioned in the introduction, there is an increased concern by the general public of the need to reduce pollutant emissions from transportation activities. This has lead to changes in the way transportation engineers model urban traffic problems and changes in the objective functions in traffic assignment. Thus far, it was shown that the generalized cost function includes only travel time or from the previous section, includes out-of-pocket cost such as costs incorporated in a toll charge. However, it is entirely possible for traffic engineers to apply vehicle emissions or noise pollution models into the generalized cost function. The next section examines the literature in vehicular and noise pollution models. First background information about vehicular pollution is presented. Second, research towards determining appropriate pollution models to represent the current vehicle fleet is summarized. Finally, an overview of noise pollution and noise pollution models is discussed.

2.5.1 Air Pollution Overview

Road transportation is one of the major sources of air pollution and contributor to the greenhouse effect. Sources of air pollutants may be classified as stationary or mobile. Stationary sources of air pollutants originate from factories whereas mobile sources are attributed to transportation activities. This section focuses on emissions from mobile sources, mainly from internal combustion engine vehicles (ICEV). The pollutants emitted from vehicles originate from the exhaust stream, brakes, tires, crankcase and the carburetor. The major pollutants normally emitted from the exhaust are hydrocarbons, carbon monoxide, nitrogen oxides, Sulphur oxides and particulates. Other pollutants such as asbestos are produced from the vehicles brakes. The crankcase and carburetor are the main sources of hydrocarbon pollutants and the tires generally emit particulate matter. The effects of the major contaminants from the exhaust stream are described in the next few paragraphs.

Carbon monoxide is a colourless, odourless, tasteless gas that is produced from the incomplete combustion of fuel. The primary effects to human health may be physiological stress, impaired motor skills, visual impairment and/or death (Corbitt, 1990). In the United States, the emission of CO by vehicular traffic accounted for 54.4% of the total CO emitted in 1987 and 87.5% of the total concentration of CO in urban areas (Wang et al., 1990)

Hydrocarbons are compounds of carbon and hydrogen that originate from the incomplete combustion of petroleum products used to fuel motor vehicles. Hydrocarbons emitted by motor vehicles accounted for 46.4% of the total HC in urban areas in 1987 (Wang et al., 1990). HC are promoters of photochemical smog and may cause eye irritation or damage to plants.

The main NO_x contaminants produced from vehicular emissions are nitric oxides (NO) and nitrogen dioxide (NO_2). The quantity of nitrogen oxide emitted is a function of the nitrogen and oxygen concentration, reaction time and temperature within the vehicle's cylinders. NO_x emissions are formed by the oxidation of atmospheric nitrogen. The effects to nature and human health may include damage to vegetation, reduced visibility, and/or respiratory problems. In the United States, it was recorded in 1987 that the NO_x

emissions from ICEV were 33.8% of the total emissions of nitrogen oxides and in urban areas vehicles contributed to 60% of the NO_x emissions (Wang et al., 1990).

Particulate matter is usually referred to as a solid or liquid matter of organic or inorganic compounds that is suspended in the air. Particulates that are released from vehicles may consist of carbon compounds or Sulphur dioxide.

The main components of Sulphur oxides are Sulphur dioxide and Sulphur trioxide. These compounds originate from the combustion of fuel that contains Sulphur in the presence of air. The Sulphur oxides react with the moisture in the air to form Sulphuric acid, a main component to acid rain. Sulphuric acid is damaging to plants, lakes and fish. The Sulphur oxides also are contributors to respiratory and visibility problems. In urban areas in the United States, SO_x emissions from ICEV accounted for 29% of the total Sulphur oxide emissions.

In general, the air contamination by vehicles is dependent on the vehicle characteristics such as engine type and size, age of the vehicle and maintenance, driving conditions and weather. Driving conditions for example, may include the vehicles' average speed. In general, as the speed increases HC emissions decrease while NO_x emissions increases and CO emissions increases up to a certain speed and then decreases again. In stop and go traffic, CO and HC emissions are always high especially during acceleration, deceleration and idling. NO_x emissions, however, do not seem to be affected in congestion (Hassounah and Miller, 1992).

Cold weather also affects the amount of contaminants released from a vehicle. If the engine is cold, the fuel does not vaporize as well and passes to the exhaust stream. It has also been found that catalytic converters do not function well in the cold. Cold engines emit more HC and CO into the air. Other weather conditions such as wind and wind direction affect the concentration of pollutants in a given area. In higher winds, the pollutants tend to dissipate and reduce the concentration of the pollutants for a given area.

2.6 Fuel Consumption Models

Vehicle emissions are directly related to fuel consumption. Fuel is required for a vehicle to overcome air and rolling resistance while maintaining the vehicle at a given speed. Fuel consumption is directly related to the age of the vehicle, the roadway system and driver behaviour. This has lead to a wide variety of fuel consumption models developed over the last thirty years. These fuel consumption models can be categorized as instantaneous models or average speed models. Instantaneous models relate fuel consumption based on speed variations over the entire trip length whereas average speed models determine fuel consumption on an average speed developed during a trip.

2.6.1 Instantaneous Fuel Consumption Models

There are several forms of the instantaneous fuel consumption model. The drive mode fuel consumption model (Ratcliffe et al., 1989) takes into account the variation in fuel consumption based on travel distance, time spent delayed and speed that a vehicle encounters during a trip. The model is expressed in the form illustrated in Equation 2.19.

$$F = f_1L + f_2D + f_3S + \ldots \qquad (2.19)$$

Where:

F = Total fuel consumed (Litres)
L = Total distance travelled (veh-km)
D = Total delay (v-h/h)
S = Number of vehicle stops
f_1, f_2, f_3= Coefficients to convert traffic behaviour to fuel consumption

Another form of the instantaneous fuel consumption is found in the NETSIM model (Hurley et al., 1981). In the model, average speed, idling and speed change cycles are considered. The fuel consumption is in an empirical form that was developed based on collected fuel consumption data in the late 1960's. The NETSIM program has incorporated several important assumptions into its program. The program assumes that the fuel consumption rate is never less than the idling rate and that for deceleration rates less than -0.3 m^2/s, fuel consumption is equal to the instantaneous idling consumption rate. Furthermore, the NETSIM program fuel consumption function is only valid for urban speeds and is shown in Equation 2.20.

$$g = 16.117 + .1658V + 0.0252V^2 + 9.626a - 0.009577aV^2 + 0.20845a^2V \qquad (2.20)$$

Where:

g = instantaneous fuel consumption rate (gal/100000 s)
a = instantaneous acceleration rate (ft/s)
V = instantaneous velocity (ft/s)

The Power Model (Post et al., Kent et al., 1982) has also been used by researchers to determine instantaneous fuel consumption rates. This model attempts to define the relationship between the fuel consumed and the power or energy required by the vehicle. The original power model is illustrated in equation 2.21.

$$f_t = \alpha + \beta P_T \qquad (2.21)$$

Where:

f_t = Instantaneous fuel consumption rate (mL/s)
α = idle fuel consumption rate (mL/s)
β = Average efficiency factor (mL/s/kW or mL/kJ), varies as a function of speed and acceleration rate.
P_T = Total power required (kW)

2.6.2 Average Speed Model

A common average speed model used by traffic engineers is illustrated in Equation 2.22. This model has been shown to be effective at low and medium average speeds less than 55 km/h. The a parameter is the idle fuel rate of the vehicle and is related to the vehicle engine displacement (EC). The b parameter is related to the vehicle tractive power (i.e. drag, inertia, road gradient)

$$f = \frac{a}{V} + b \qquad (2.22)$$

Where:

f = Vehicle fuel consumption per unit distance (mL/ km)
V = Average speed (km/h)
a, b = Parameters usually obtained by regression (a, mL/h, b, mL/km)

Average speed models can also be derived by determining the fuel consumed based on a constant speed that is also dependent on rolling and air resistance and idling. The form of the function is shown in Equation 2.23.

$$f_c = b_1 + \frac{b_2}{v_c} + b_3 v_c^2 \qquad (2.23)$$

Where:

f_c = fuel consumption per unit distance (mL/km)
v_C = Constant cruise speed (km/h)
b_1, b_3 = Constants derived from the rolling and air resistance
b_2 = Constant that is related to idling fuel consumption

2.7 Vehicle Emission Rate

The TRANSYT 7F- Model has incorporated vehicle consumption and emission rate functions in its program. The general form of the function is shown in Equation 2.24a). This function is used to determine vehicle pollution levels based on the vehicle's average speed. Equation 2.24b) and 2.24c) define that rate of production of pollutants for vehicles during acceleration/deceleration and idling mode, respectively. The parameters A, B, and C have been defined for different driving conditions such as acceleration, deceleration and constant travel speeds, and different grades. These parameters are defined by Penic and Upchurch (1992).

$$ROP = \frac{Ae^{Bv}}{Cv} \qquad (2.24a)$$

$$ROP_{accel} = \frac{10^B (v_f^A - v_i^A)}{C}$$

$$ROP_{decel} = \frac{10^B (v_i^A - v_f^A)}{C} \qquad (2.24b)$$

$$ROP_{idling} = d \qquad (2.24c)$$

Where:

ROP = Rate of production (g/ft or gal/ft)
v = Average vehicular velocity on link (ft/s)
v_i = Initial velocity (ft/s)
v_f = Final velocity (ft/s)
A,B,C = Constants
d = Constant rate of production (g/s or gal/s)

An instantaneous power demand emission rate model for determining nitrogen oxide and hydrocarbon emission rates have also been developed by researchers (Post, Kent et al., 1984). The function is defined in Equation 2.25 and was derived by empirical data collected on a test vehicle. They found that nitrogen oxides and hydrocarbon emissions vary linearly with power similarly to the power demand model for fuel consumption shown in Equation 2.21. The function, however, cannot be used to determine carbon monoxide emission rates because it was found that carbon monoxide emission rates do not show a simple linear relationship to power. The α and β parameters in the equation are related to the vehicle characteristics.

$$HC = \alpha + \beta Z_{tot} \tag{2.25}$$

Where:

Z_{tot} = link averaged total power (kW)

2.8 Noise Pollution Overview

Similar to vehicle pollutants, the increase in vehicular noise pollution is a concern of the general public. During the last two decades there have been numerous efforts undertaken in North America, Europe and Asia to reduce noise pollution. Historically the primary tools have consisted of stricter noise policies and regulations which have resulted in quieter vehicular engines and quieter tire/roadside interaction. Another popular method has been to limit access to the highest noise producers (i.e. heavy trucks) to specific routes in order to minimize noise pollution. It has been hypothesized that with recent advances in electronic toll collection and route guidance capabilities, it is now feasible to directly influence heavy vehicle route selection so as to obtain noise abatement benefits. This next section will briefly define noise and describe research towards modelling noise pollution in an urban environment which will be later used in Chapter 5.

Noise pollution can be defined as "unwanted" sound and this sound is mainly generated by the power system of the vehicle and the tire friction against the road. The sound from the power system and the vehicular tires create a disturbance in the air which generates a pressure wave and vibration. As the sound vibration travels through the air, it collides with other molecules in a chain-reaction manner from one molecule to another. The colliding molecules produce an increase or compression in the air which causes the sound wave to move outward. The outward movement of the sound is similar to the waves generated when a pebble is thrown in water.

Noise is typically measured in decibel units (dB). The decibel scale, which is a power scale, has been adopted in order to quantify the large range of noise levels. In most applications the decibel scale is weighted so as to more accurately describe the human perception and response to a sound. The typical unit used to describe traffic noise is known as the decibel A scale (dB(A)). This weighted noise level filters out some of the frequencies of sound in a manner similar to the response characteristics of the ear. Traffic noise is usually measured at the percentile level and there are three basic measures used: L_{10}, L_{50}, L_{90}. For example, the value of L_{10} is the level of noise at a particular point that is exceeded 10% of the time. Another common unit for measuring noise is known as the equivalent sound unit (L_{eq}). The equivalent sound level is defined as the constant sound level that has the same energy as a time-varying noise level for a specified time duration.

The Ministry of Environment of Ontario (1987), predicts traffic noise levels (L_{eq}) by analyzing a representative sample for two time periods. The time durations are divided into day and night. The daytime hours last from 7 a.m. to 11 p.m. and the nighttime hours are from 11 p.m. to 7 a.m. Allowable equivalent sound level limits have been set by the ministry and are outlined in Table 2.1. The sound level limit is dependent upon the duration of the noise and intensity. As an example, if the allowable noise level is 69 dB(A) for 6 hours, then the allowable noise level for 12 hours would be 66 dB(A) (MOE, 1987). The effect of noise level duration and intensity is important in determining the noise level limits from vehicular traffic. Typical noise levels for light vehicular traffic is 75 dB(A) and for heavy vehicles the noise levels may be as high as 80 dB(A) at the source (MOE, 1987). When these values are compared with the allowable limits for other noise sources as shown in Table 2.1, the difference are quite significant.

Table 2.1: Equivalent Noise Levels

Land Use/ Activity	Equivalent Sound Level Limits (L_{eq}) dB(A)
Bedroom, hospitals (Time 23:00 - 7:00)	40
Living room, hotels, etc. (Time 7:00 - 23:00)	45
Classrooms, offices, conference rooms (Time 7:00 - 23:00)	45
Reception areas, retail stores (Time 7:00 - 23:00)	50
Outdoor living areas (Time 7:00 - 23:00)	55
Light vehicular traffic	75
Heavy vehicular traffic	80

Traffic noise fluctuates with time and varies according to road surfaces, traffic flow, speeds, percentage of light, medium, and heavy vehicles, distances to building facades, weather and land uses. For example, the noise level can increase significantly with an increase in heavy vehicles on the roadway (Jraiw, 1992). Noise levels are also affected by the distance between the noise source and the measurement source.

Noise exposure models developed in Australia (Jraiw, 1992) attempt to relate equivalent sound units to vehicular traffic. In the model, the noise levels fall into two categories: Noise produced in urban areas where average speeds are 50 km/h or less and noise produced in outer urban areas where speeds are can reach as high as 80 km/h. Equation 2.26a) shows the former case and Equation 2.26b) shows the latter case.

$$L_{eq} = 54.9 - 6.11 Log_{10} V - 5.51 Log_{10} F - .01 J + 11.7 Log_{10}(L + 6M + 10H) - 4.01 Log_{10}(d - k)$$

(2.26a)

$$L_{eq} = 56.5 - 6.53 Log_{10} V + 11.6 Log_{10} Q + .17 P - 6.48 Log_{10} F - .01 J - 2.47 Log_{10} N \qquad (2.26b)$$

Where:

L_{eq} = energy equivalent sound (dBA)
V = mean speed of traffic (km/h)
F = distance between measurement point and farside building facades (m)
J = distance from the relevant junction (m)
L = volume of light vehicles (v/h)
M = volume of medium vehicles (v/h)
H = volume of heavy vehicles (v/h)
d = distance between nearside curb and nearside facade (m)
k = distance between measurement point and nearside curb (m)
Q = traffic flow (v/h)
P = percentage of medium and heavy vehicles
N = distance between measurement point and nearside facade (m)

The above equations show that the noise level at a particular measurement point will increase with an increase in traffic flow, and percentage heavy trucks. However, the noise levels will decrease as the distance to the building facades and traffic junctions get larger. In both models, noise levels will decrease with an increase in speed.

The Ontario Ministry of Transportation has also done some work on predicting noise levels. A traffic noise prediction model based on empirical data that relates equivalent sound units to vehicular traffic is shown in Equation 2.27 (Hajek and Krawczyniuk, 1983)

$$L_{eq} = 21.5 + 11.1 * \log(V_c + 10V_{MT} + 15V_{HT}) - 15.4 * \log D + 15.0 * \log S \qquad (2.27)$$

where:

L_{eq} = Equivalent sound (Decibels)
V_c = Volume of cars (v/h)
V_{MT} = Volume of medium trucks (v/h)
V_{HT} = Volume of heavy trucks (v/h)
D = Distance from houses to roadway (m)
S = Average operating speed (km/h)

2.9 Conclusions

1. Equilibrium and non-equilibrium techniques have been used extensively in traffic assignment models. Although, the non-equilibrium methods are simple to use, they are heuristic in nature and a true optimal solutions are not guaranteed. Equilibrium models are more realistic in that they assume route travel costs change with flow. The convex combinations algorithm developed in the 1970's always identifies the optimal solution.

2. Traditional traffic assignment models have been generally used to determine route flows when the objective is to minimize the users' travel time on the network. Due to the changes in the public's perception on the environment and changes in technology, it may be possible to implement ITS technologies to route traffic such that vehicular or noise pollution is minimized. Because traffic assignment models are based on the concept of generalized cost, the traditional traffic assignment techniques may be applicable for analyzing assignment problems which use ITS technologies to route traffic from environmental perspectives. The only changes required would be to identify the appropriate cost functions.

3. Vehicle pollution models are directly related to the age and type of the vehicle, the roadway system and driver behaviour. This has lead to a wide variety of fuel consumption and emission cost functions developed over the last 30 years. However, little research has been done on analyzing the effects of traffic routing based on environmental objectives on a realistic network.

4. There is a need for a general macroscopic computer model to evaluate environmental objectives in traffic routing strategies. This need is becoming more apparent as the implementation of route guidance or electronic toll collection systems is becoming technologically possible in North America.

Chapter 3 - Validation of the ASSIGN model program

3.0 Introduction

The objective of any traffic assignment model is to accurately determine link flows and travel times on a network given real world conditions. One of the problems often confronted in modelling urban areas is the method by which the network may be represented. These problems include determining the most appropriate method to model link connections, or deciding on the correct link saturation flows and speeds within the network. There are some advantages and disadvantages in the way existing computer programs model real networks. Computer models such as CONTRAM use a link based system to model connections between links whereas other programs similar to ASSIGN are node based.

The ASSIGN model, developed at the University of Alberta for internal research purposes only, is used in this thesis because commercial traffic assignment models such as CONTRAM do not allow for the code to be available in order to make adjustments in the traffic routing objectives. In this thesis, research towards routing traffic under environmental and equity objectives is examined and therefore, a model is required to accurately determine link flows on a network when the generalized cost functions are based on environmental conditions.

Many transportation agencies and firms use either existing computer models or develop their own based on their needs. The City of Edmonton, for example, uses CONTRAM to model detailed road improvement projects or individual project developments at a tactical level for a sector of a larger urban network (Brownlee et al., 1988). They have a well established data base representing the different areas of the city of Edmonton in a CONTRAM network format. In this thesis, the CONTRAM network data files for the University network, obtained from the City of Edmonton, are converted to an ASSIGN model format such that the files may be used to route traffic based on environmental and equity objectives.

This chapter describes the advantages and disadvantages between a link based and node based system. The approach used in converting the CONTRAM University network to a format appropriate for the ASSIGN model program is discussed. The major differences between the two models will be outlined along with assumptions to the ASSIGN input data files will be described. Furthermore, a calibration technique for the ASSIGN program is described such that the link flows from the ASSIGN program may be compared with surveyed and CONTRAM data for the University network.

3.1 The University Network

A network representing the University area of the City of Edmonton is used to validate the ASSIGN model. This network will subsequently be used in all other chapters to examine traffic routing strategies under environmental and equity objectives. Figure 3.1 shows a map of the City of Edmonton and enclosed in the box is the University area which represents an area of approximately 6.5 km^2. The north and west side of the University network is bounded by Saskatchewan drive, the south side is bounded by 61 Ave. and the east side bounded by 99th Street. The coded network is illustrated in Figure 3.2. It is grid shaped and consists primarily of arterial and major collector roadways.

The original network input data files were provided in a CONTRAM format by the City of Edmonton. The input data files included information about the network characteristics, O-D demand and signal control data. These files were converted into an ASSIGN model format.

For analysis purposes, the a.m. peak hour is modelled. Most of the trips are home to work where the majority of the people are heading towards the University area or through this area to reach Downtown from south Edmonton. The morning peak hour is chosen because it is less diverse than the afternoon peak due to the fact that drivers must get to work at a specified hour. Furthermore, it is found that only slight delays occur on the major arterials and therefore very little oversaturated conditions appear on the network. In this case, a steady state static model is appropriate for routing traffic within the network.

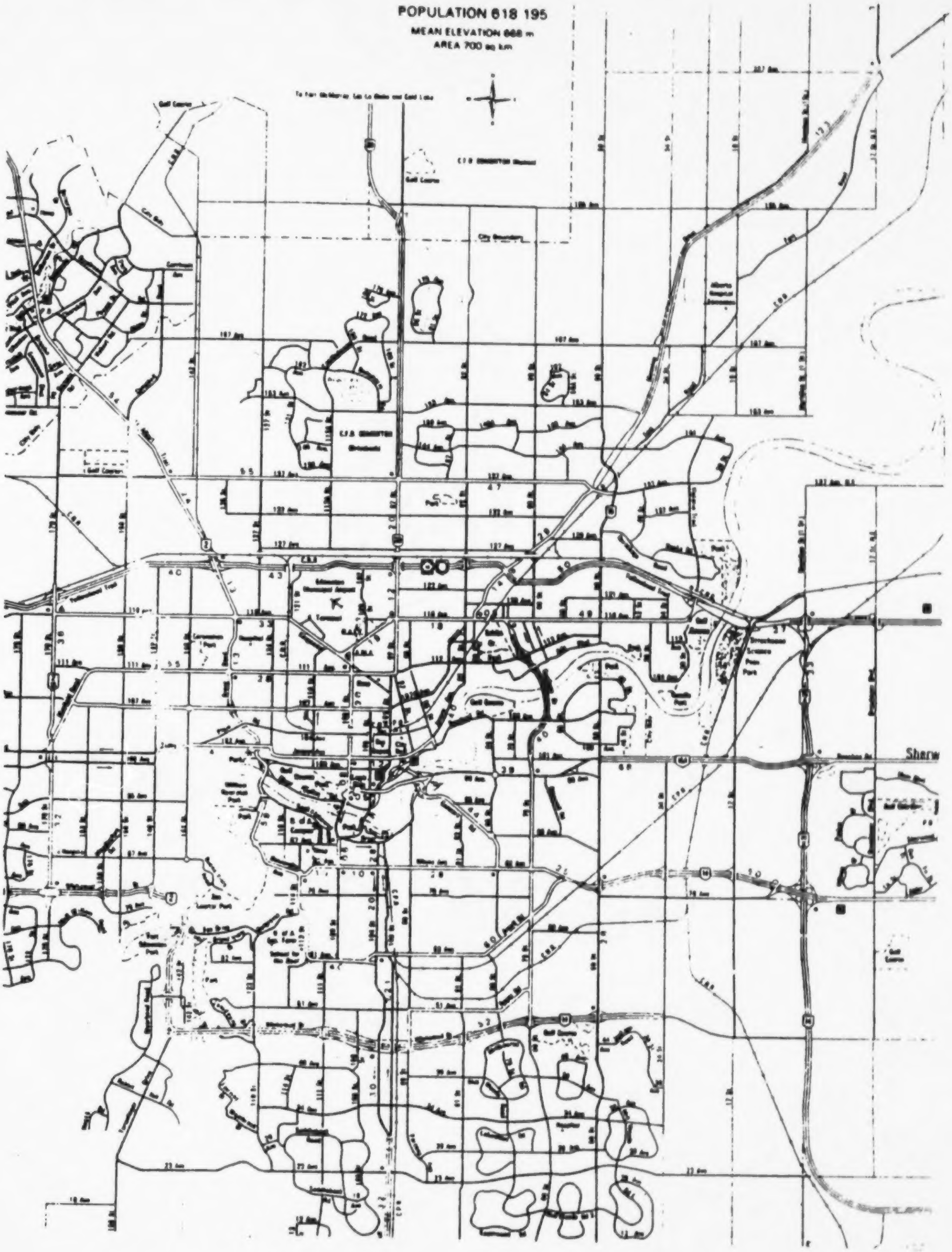

POPULATION 618 195
MEAN ELEVATION 668 m
AREA 700 sq km
Sherw

Figure 3.1 - Map of the City of Edmonton

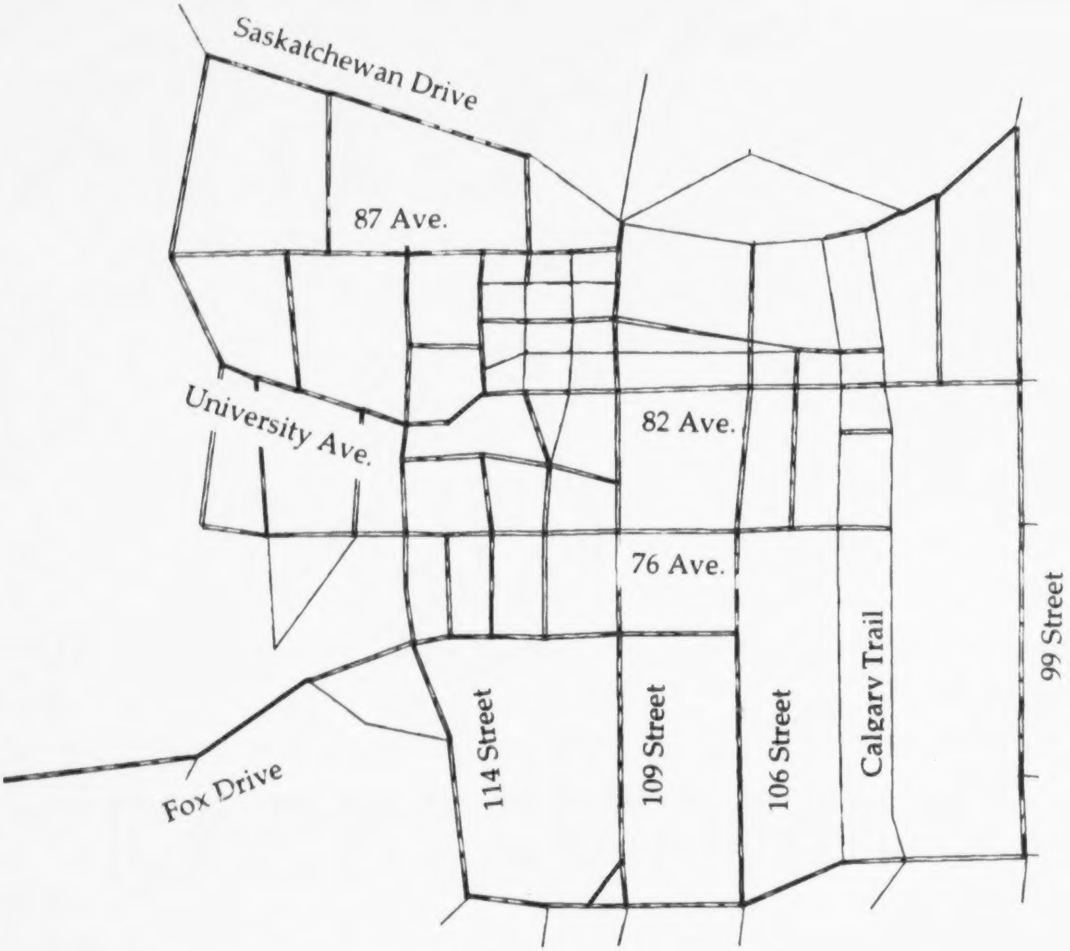

Saskatchewan Drive
87 Ave.
University Ave.
82 Ave.
76 Ave.
Fox Drive
114 Street
109 Street
106 Street
Calgary Trail
99 Street

Figure 3.2 - University Network

3.2 Brief Description of the CONTRAM and ASSIGN Input data Files

The CONtinuous TRaffic Assignment Model, normally known as CONTRAM is a traffic assignment model used to model traffic management schemes in urban areas (Leonard et al., 1982, 1989). The main inputs to the program are the O-D demand, the traffic network characteristics such as link connections, free flow travel times, link capacities etc., and the network control data which describe the signal timing plans and fixed route data.

The input data files in CONTRAM are specified by card type. Card type 1 defines the duration of the simulation and time intervals. Card type 3 lists the links that connect the origin. Card type 4 outlines details required for the uncontrolled links such as the link number and the number of the downstream link or destination, the cruise time, the link length, saturation flow, storage capacity and the number of the "to" node for that link. Card type 5 describes the details for give-way (stop controlled) links. The link length, cruise time, saturation flow and to-node, is coded in the same format as in card type 4, however, the gradient relating the throughput capacity of the give-way link to the total demand is also included. Finally, card type 6 lists information about the signalized links.

ASSIGN is a general macroscopic traffic assignment model. The vehicles are assigned to certain paths based on user specified flow dependent generalized cost functions and user specified origin-destination demand rates. The model is capable of routing traffic under user or system optimal principles for static/deterministic and static/stochastic conditions. ASSIGN may be used to act as a supporting module for the simulation model INTEGRATION (Van Aerde, 1992). However, it is not necessary to have or use the INTEGRATION model in order to use ASSIGN to estimate traffic flows, link travel times and aggregates statistics.

The main inputs to the ASSIGN program are: 1. The simulation data; 2. The network characteristics; 3. The signal control data; and 4. The dynamic O-D demand. The simulation data file identifies the time periods, simulation time, and the location of the input and output files. There are two files that describe the characteristics of the network. The first file is the node file which describes the location of the node relative to a reference point and describes the type of node for each location. For example, a node at an intersection may be an origin/destination node or a node that separates the links between intersections. The second file is the link characteristic file which is similar to CONTRAM where information about the network such as the link length, saturation flow, free flow speed, etc. is listed. The signal control file specifies for each signal, the plan number, plan duration, the green time and lost time. Finally, the dynamic O-D demand file lists the demand level for each O-D pair where each demand rate is given a specific time interval. However, the demand file for the University network is static and therefore the total demand for the a.m. peak hour does not change with time. It should also be noted that a detailed description of the ASSIGN model program is provided in Appendix A.

3.3 Differences Between CONTRAM and ASSIGN Input Data Files

As already mentioned in the introduction, CONTRAM is a link based model whereas ASSIGN is node based. Consequently, each model specifies the link connections within the network differently. ASSIGN models link connections by specifying from- and to- nodes for each link whereas CONTRAM lists the downstream links options for a vehicle arriving at any particular link. The following is a brief outline of the differences between CONTRAM and ASSIGN. The methods of modelling stop controlled and signalized intersections, link connections and zones are discussed in the following sections.

3.3.1 Modelling Stop Controlled and Signalized Intersections

ASSIGN and CONTRAM model controls at intersections by a link based method where for each link, a control is assigned. CONTRAM has built in three types of controls on a link. The links can be either uncontrolled links, give-way links (stop controlled links) or fully signalized links. Uncontrolled links are modelled in the same manner for each program.

The CONTRAM program models give-way links by reducing the saturation flow by a gradient value, (f) inputted by the user. Equation 3.1 shows how CONTRAM models throughput capacity for a give way link. However, the ASSIGN program models stop controlled links by specifying a constant travel time penalty of 20 seconds and reductions to capacity or gap-acceptance behaviour is not included.

$$Q = q_s - fq \tag{3.1}$$

where:

Q = Throughput capacity
q_s = Saturation flow
f = gradient
q = controlling flow

Signalized links at intersections for both CONTRAM and ASSIGN are also modelled differently. The City of Edmonton is using CONTRAM 4.0 to model the University network where phases that occur simultaneously on a link are modelled by including a percentage of stage time greater than 100. In ASSIGN, two simultaneous phases can be explicitly modelled whereby the simultaneous phases are identified in the link characteristics file and the time allotted to the phases is specified in the signal control file. Due to the fact that simultaneous phases are not explicitly modelled in CONTRAM, it was necessary to modify CONTRAM's definition of simultaneous phases. It was assumed that links with stage times over 130% were involved in a two phase operation if the phase number following the original phase did not conflict with the signal timing of the opposing traffic flow. For example, if a particular westbound link had a percentage stage time of 140%, a two phase operation would exist if phase numbers 1 and 2 were used to identify the signal timing for links in a similar direction (i.e. E-W or W-E). However, if phase number 2 was used to identify the signal times for the opposing traffic flow (i.e. N-S or S-N), then only one phase would exist on the westbound link.

CONTRAM 4.0 and ASSIGN also determine the length of the intergreen time differently. CONTRAM assigns the total lost time or intergreen time for the entire cycle length of each signal according to the data coded from card type 7. ASSIGN models the lost time interval as an explicit number for each phase of the signalized link in the signal control file. It was assumed that the total lost time identified by card type 7 in CONTRAM was equivalent for each individual phase. For example if the signal had 3 phases and the total lost time specified in CONTRAM was 15 seconds, the intergreen time for each phase would coded as 5 seconds in the ASSIGN signal control file.

3.3.2 Modelling Links

It is also important to specify as accurately as possible the appropriate link saturation flows, speeds, number of lanes, and turning movements that occur at an intersection in a computerized network. The number of lanes, and turning movements can be easily identified by existing information about the study area. However, link speeds and saturation flows are sometimes difficult to determine and mimic in a computer model.

Engineering judgment is usually entailed in determining speeds and saturation flows at different intersections within a network.

This section identifies the differences between the concepts of a node based and link based system for modelling links in an urban network. There are two possibilities for ASSIGN to mimic the CONTRAM network characteristics file. The first is labelled as the "CONTRAM" method and the second is called the 8-node coordinate system. The 8-node coordinate system can be further categorized by the following acronyms: The "short artery" method; the "long artery" method; and the "combined" method. These categories are later described in detail. However, first the drawbacks of the "CONTRAM" method for a node based program are described. This is followed by describing the purpose of the 8-node coordinate system and the differences between the three methods.

In CONTRAM, each lane that has the same characteristic is modelled by one lane where the saturation flows take into account the possible multiple lanes of a "real" network at an intersection. Furthermore, if a lane such as a turning movement has a different saturation flow, the link is modelled separately within CONTRAM where the different saturation flows would be identified by the user for the turning movement as well as the straight through movement for the links arriving at the same to- node. Similarly, in ASSIGN, it is possible to model lanes with different saturation flows for the links that approach the same intersection (or node). However, vehicles will tend to use the link with the highest saturation flow due to the nature of a node based system as shown in the next few examples.

As already mentioned, CONTRAM models major turning movements by a separate link. In a link base system, the next link that a vehicle is allowed to take is identified by a list of downstream links in the network characteristics file. This is shown in Figure 3.3b where a sample link characteristic file is illustrated for CONTRAM and ASSIGN for link number 4352 illustrated in Figure 3.3a. Figure 3.3a is a schematic diagram that illustrates the convention used in the University network to identify links approaching a node. The link convention easily identifies the type of link and its relative direction. For example, links ending in numbers 1, 2, 3, 4 represent straight through movements that may also have the possibility of making left or right turns. Links in the

4000 range represent explicit right turn movements and links ending in numbers 5, 6, 7, and 8 represent left turn movements only.

It is shown in Figure 3.3a that each link in the E-W direction has the same to-node. Because CONTRAM is link based, a vehicle making a turn will therefore use the appropriate lane. In the example, link number 4352 would be followed by link number 163 in the CONTRAM network characteristics file as indicated in Figure 3.3a and 3.3b. Link number 4352 leads to node 16 which is the immediate node following node 35 in a southerly direction. In ASSIGN, the same link would not have a specified downstream link number describing link 4532 in the network characteristics file. Only the from- and to- node would identify the location of the link relative to the others. It is shown in Figure 3.3b that vehicles using link number 4352 in ASSIGN are not explicitly required to turn right because the next link (i.e. link number 163) is not identified in the file.

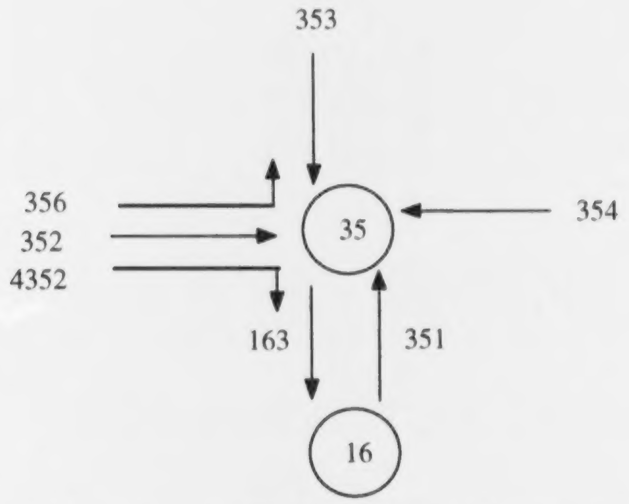


Figure 3.3a - Schematic Diagram Showing Link Number Representation for the University Network

CONTRAM

6 4352 163 31 510 1650 35 2 164

Field 1	Card number
Field 2	Link number
Field 3-5	Number of downstream link (Blanks indicate no other downstream links)
Field 6	Link travel time (seconds)
Field 7	Link length (m)
Field 8	Saturation flow (v/h)
Field 9	Signal number
Field 10	Phase number
Field 11	Percentage of stage time greater than 100

ASSIGN

4352 89 35 0.49 59 1650 1 0 1 1 35 2 3 0 1 0 Right

Field 1	Link number
Field 2	From node number
Field 3	To node number
Field 4	Link length (km)
Field 5	Link speed (km/h)
Field 6	Saturation flow (v/h)
Field 7	Number of lanes
Field 8	Platoon dispersions (not used)
Field 9	α parameter
Field 10	β parameter
Field 11	Signal number
Field 12	Phase number
Field 13	Phase number
Field 14	HOV lane indicator (not used)
Field 15	Surveillance number
Field 16	Roadway Toll Charge ($/v)
Field 17	Link Description

Figure 3.3b - Link Characteristic Files for CONTRAM and ASSIGN

Therefore, if the CONTRAM network files are blindly used to represent the network in an ASSIGN format, then explicit turning movements that have the same to-node as the straight through links may by avoided by the turning vehicles because of the tendency for the turning links to have lower overall saturation flows. Similar to the explicit right turn, Figure 3.3a shows that left turning vehicles are required to use link number 356. However, due to the fact that ASSIGN is node based, the vehicle could use link number 352 to make the left turn. If all vehicles making a left turn were to use link number 352, flows and link travel times would not be representative of the real world. To overcome this problem an 8-node coordinate system was developed. Figure 3.4 shows the 8-node coordinate system for the same intersection illustrated in Figure 3.3a. The node numbers are assigned sequentially in a counterclockwise direction starting at the bottom right with a value of one plus it original node number.

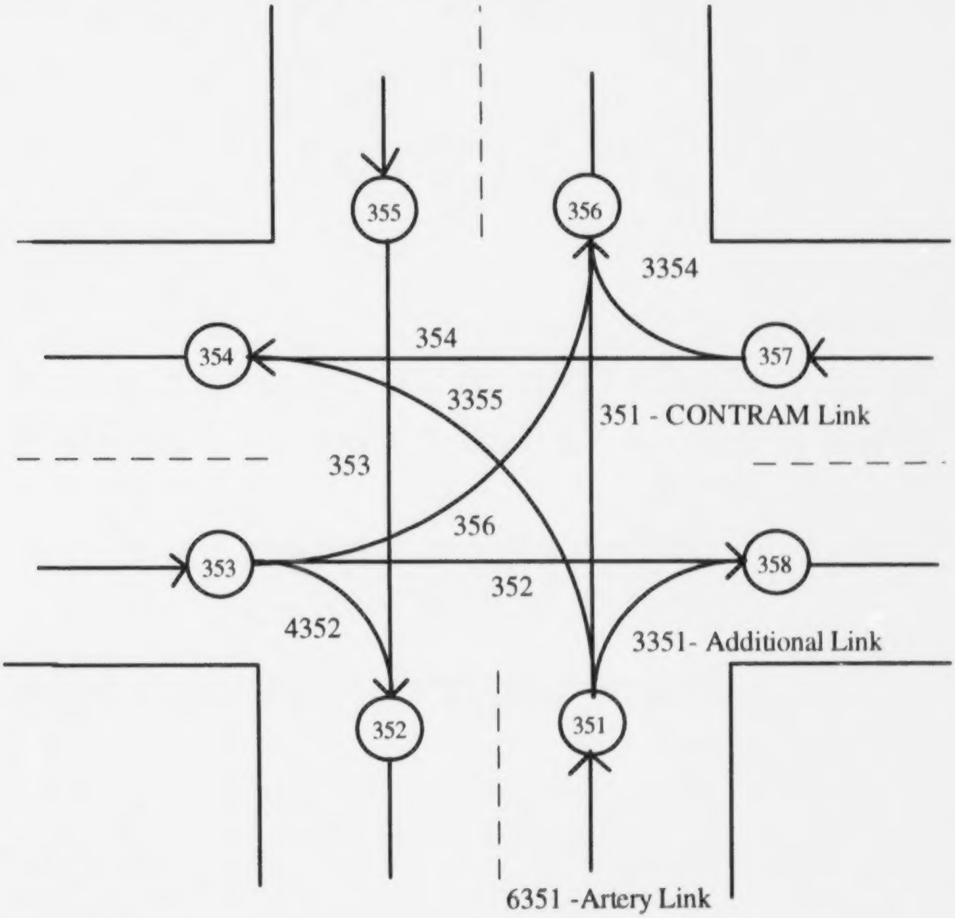

355
356
3354
354
354
357
3355
351 - CONTRAM Link
353
356
353
358
352
4352
3351- Additional Link
352
351
6351 -Artery Link

Figure 3.4 - 8-node Coordinate System

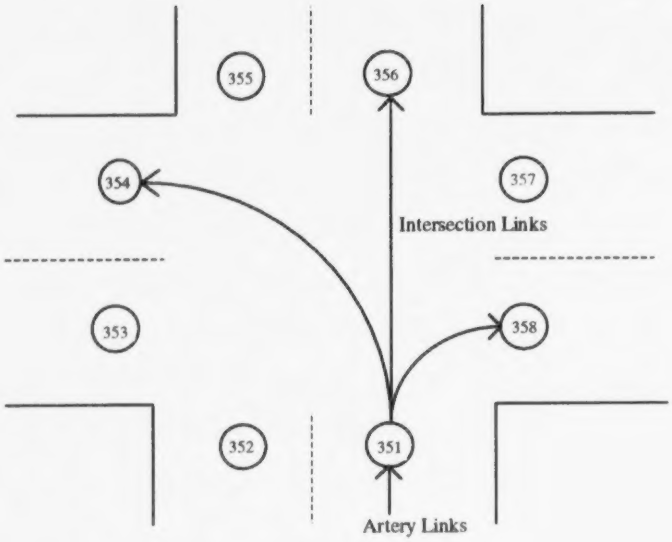
The 8-node system allows turning movements to be modelled accurately and modelled similar to CONTRAM. However, there are some notable differences between the new ASSIGN network and the CONTRAM network. One of the major differences in the ASSIGN network is that links are divided into two separate categories: Intersection links and artery links. The intersection links control the turning and straight through movements along with the signal or stop delay. These links have the same code number as in the CONTRAM network. The arteries connect the succeeding intersections links and have been given an identification code equal to the succeeding intersection link plus 6000. Moreover, these artery links are not assigned a signal number or other form of delay. For example, in Figure 3.4, the intersection link number 351 would be assigned a signal number or stop control identification number and link number 6351 would connect the preceding intersection (node 16) with link number 351. The delay experienced by the drivers on link 6351 will only exist from the travel time relationship which is dependent on the changes in the volume to capacity ratio.

One of the problems with the 8 node coordinate system is determining how link lengths and saturation flows could be modelled on links that have combined straight and right or left turn movements. In CONTRAM, straight through links could be assigned several downstream links that follow different directions. For example, link number 354 from Figure 3.3, was assigned the following downstream links: 898, 894 and 631. Link number 631 continues in a northerly direction and link numbers 898 and 894 continue in a westerly direction. In this example, vehicles that approached the intersection by link 354 had the option of continuing straight through or turning right. In effect, this method represents a minor intersection approach where drivers normally do not have a choice of using separate turning lanes due to low approach volumes.

In ASSIGN, additional turning movement links with different link numbers were created in an attempt to model the fact that right or left turns may have different saturation flows than the original straight through movements. These additional turning movements were assigned link numbers between 3000 - 4000 as shown in Figure 3.4. Furthermore, an additional right turn movement was assigned the same saturation flow as the straight through link and a left turn movement carried 1/2 the original saturation flow. The reduction in saturation flow for the additional left turn was used to represent a scenario where drivers would experience a greater travel time delay when making left turns due to the opposing traffic flow.

There are three methods as already mentioned in which the artery and intersection links could be modelled in the 8-node coordinate system. The first method, the "short artery" method, involves using very short artery links and long intersection links. This method ensures that the CONTRAM exclusive turning movements are modelled similarly in ASSIGN. The second method, the "long artery" method, involves the use of long artery links and very short intersection links while the third method is a combination of methods one and two which is called the "combined" method.

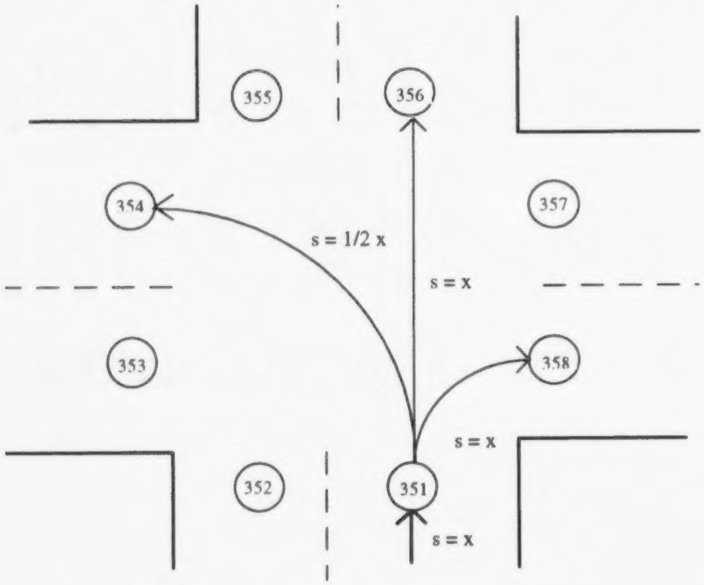
In the "short artery" method, intersection links have lengths equal to the original CONTRAM link length minus 20 m while the arteries connecting the intersections have a length equal to 20 m. Figure 3.5a demonstrates the concept of the "short artery" method. Long intersection links allow the vehicles to experience delay from signal control and average speed on the link. However, one problem with this method is the fact that there exists a large increase in capacity at minor intersections. Figure 3.5b illustrates the potential problems with using long turning link lengths for minor intersections where ASSIGN includes the additional right and left turn movements. For example, Figure 3.5b shows that if the incoming saturation flow is x v/h, the additional right and left turn would then have saturation flows of x v/h and 1/2 x v/h, respectively. This method increases the capacity of the intersection and the effect of the increase in capacity will change driver behaviour because of the reduced link travel time caused by the lower volume to capacity ratio for the right and left turning vehicles.


355
356
354
357
Intersection Links
353
358
352
351
Artery Links

Length:

Intersection Link = actual length - 20 m
Artery Link = 20 m

Figure 3.5 a) "Short" Artery Method


355
356
354
357
s = 1/2 x
s = x
353
358
s = x
352
351
s = x

s = saturation flow (v/h)

Figure 3.5 b) Illustration of Saturation Flows at a Minor Intersection

For exclusive left and right turns assigned in the CONTRAM link characteristic file, the "short artery" method is the most appropriate because the same delay and capacity on the link will be experienced as in CONTRAM. Figure 3.5c illustrates that if the intersection includes an exclusive right turn with a saturation flow of x v/h, the artery link would have a saturation flow equal to the sum of the saturation flows of the straight through link and the exclusive right turn. Moreover, if it is also possible to make a left turn from the straight through movement, then the left turn saturation flow would be equal to 1/2 the saturation flow of the straight through movement (i.e. 1/2 y v/h).

Figure 3.5d also illustrates an ideal link configuration when an intersection approach consists of an exclusive left, right and straight through movement. The saturation flow on the artery link is the sum of the saturation flows of the exclusive left, right, and straight through links. The saturation flows on the exclusive lanes are x, y and z v/h, respectively which on a relative scale would be similar to the CONTRAM description for this particular intersection.

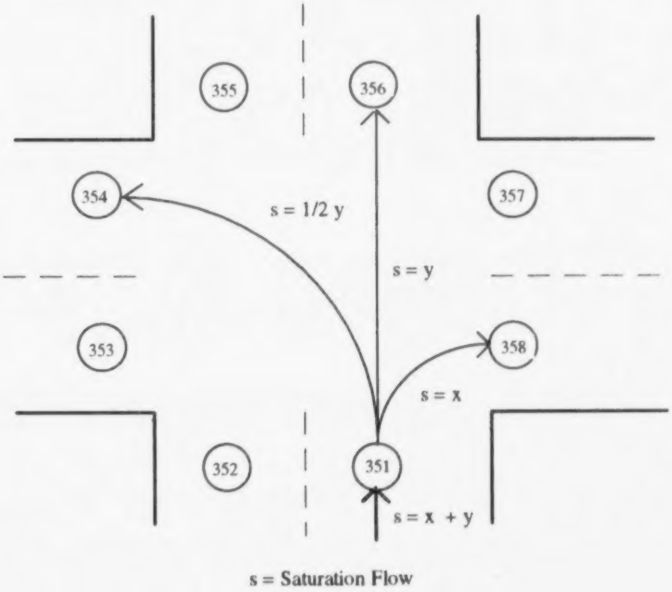


Figure 3.5 c) Illustration of Saturation Flows at an Intersection with an Explicit Right Turn

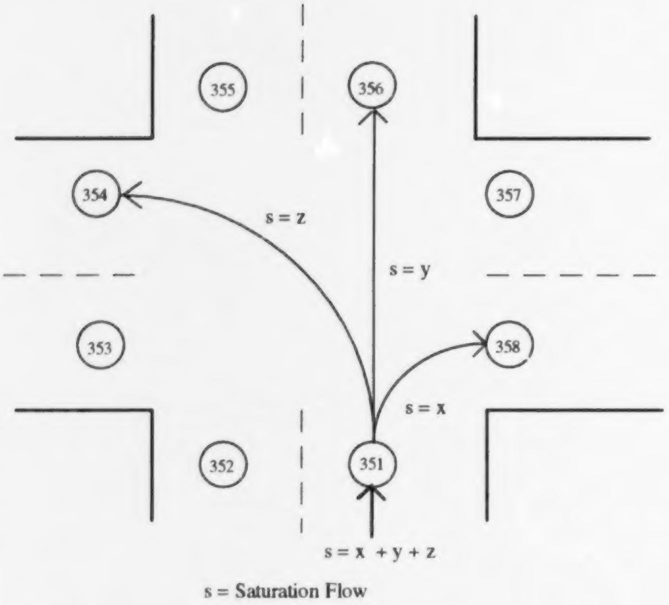


Figure 3.5 d) Illustration of Saturation Flows at an Intersection with Explicit Left and Right Turns

In the "long artery" method the length of the artery links is the actual length minus 20 m and the intersection links are 20 m long. This method is essentially the reverse of the "short artery" method and is shown in Figure 3.6a. One of the concerns of the previous method was the large increase in capacity for the vehicles that make left or right turns at minor intersections. The "long artery" method ensures that the large increase in capacity for minor intersections does not affect the overall driver behaviour (i.e. route choice) as the traffic proceeds through the intersection by the very short links. Figure 3.6b illustrates a minor intersection where exclusive left or right turns do not exist. The vehicles approaching the intersection will experience overall travel time delay as they travel on the long preceding artery links with saturation flows on the arteries equal to those described in the CONTRAM network characteristic file for the straight through movements. These vehicles will not be influenced by the large increase in capacity due to the short link lengths at the intersection.

However, Figure 3.6c illustrates the problems that may exist at intersections that have exclusive turning lanes. In Figure 3.6c, the saturation flows on the exclusive lanes are identified as x v/h for the right turn and z v/h for the left turn. The effect of the travel time delay from the reduction in capacity of a signal control will not show any apparent travel time impedance due to the short intersection links and therefore the exclusive turning lanes in ASSIGN will no longer represent the exclusive links identified in CONTRAM.

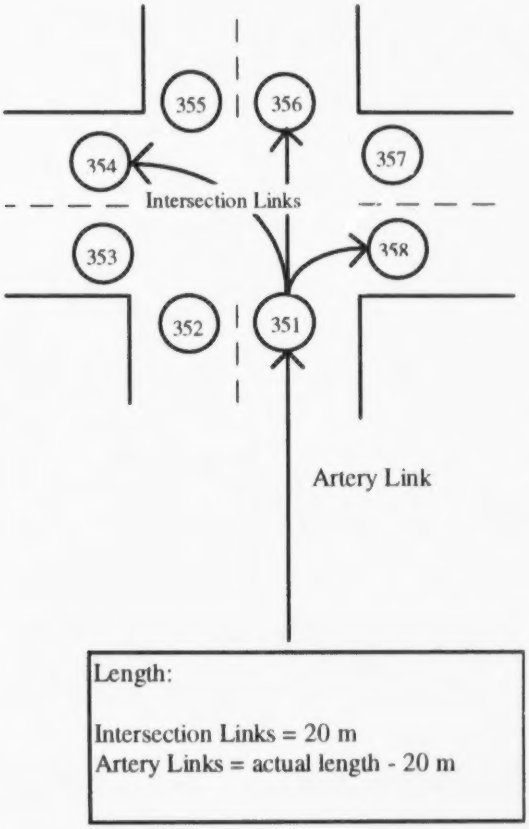
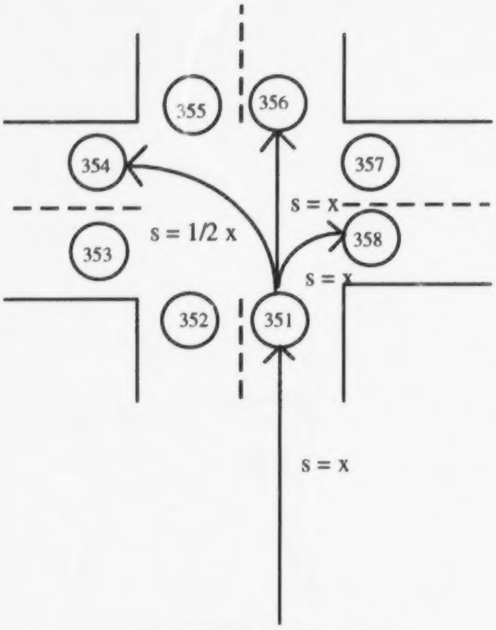
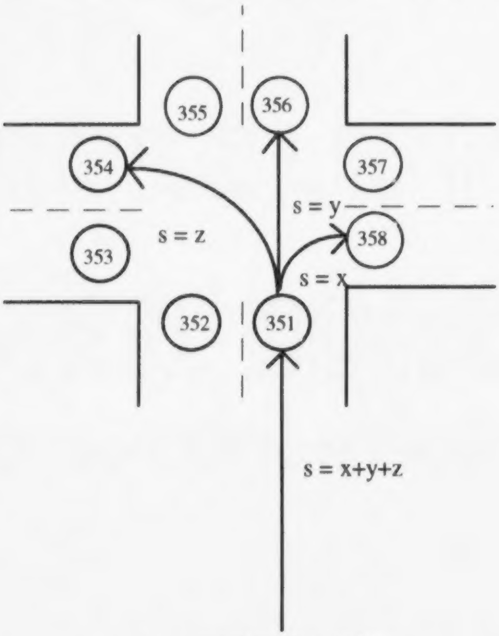

355
356
354
357
Intersection Links
353
358
352
351
Artery Link
Length:
Intersection Links = 20 m
Artery Links = actual length - 20 m

Figure 3.6 a) "Long" Artery Method


355
356
354
357
s = x
s = 1/2 x
353
358
s = x
352
351
s = x

s = saturation flow (v/h)

Figure 3.6 b) Illustration of Saturation Flows at a Minor Intersection


355
356
354
357
s = y
s = z
353
358
s = x
352
351
s = x+y+z

s = saturation flow (v/h)

Figure 3.6 c) Illustration of Saturation Flows at an Intersection with Explicit Left and Right Turns

The "combined" method combines methods one and two based on whether or not there exists exclusive left or right turns. If an intersection includes an exclusive left or right turn, it is more appropriate to use a long intersection link and a short artery link - method one. In this case, the ASSIGN network would be consistent with the CONTRAM network where delay from a signal or stop control and delay from the time spent on the link is experienced by drivers using the exclusive link to make a turn. However, the "long artery" method is more appropriate for movements at minor intersections where these intersections may include left or right turns allowed by a single straight through link and not by exclusive lanes. The short links at the minor intersections will have no effect on driver behaviour and the large saturation flows at the intersection will be countermeasured by the longer arteries that have saturation flows equal to the succeeding straight through link. The "combined" method is theoretically sound due to the fact that both methods are being used depending on the situation at the intersection.

One final problem that engineers are confronted with is determining the appropriate speed on the links. In ASSIGN, free flow travel speeds are recorded in the network characteristic file. The City of Edmonton assigned the same free flow travel speed on the links with similar to-nodes and direction. The non calibrated free flow travel speeds on the network in CONTRAM ranged from as high as 72 km/h to as low as 22 km/h. In ASSIGN, the speed on the artery links were therefore equal to the travel speed of the links of the succeeding intersection.

3.3.3 Modelling Zones

In general, zones are located at major traffic generators or attractions. The University network has two types of zones: internal and external zones. Each zone in the University network is identified by two codes. If the zone is both a traffic generator and attractor, then, CONTRAM models the origin and destination by a separate code. Origin nodes, for example, are coded as node numbers between 500 and 600 and each destination is coded as a value greater than 8000. In order to reduce the program memory requirements in ASSIGN, the zones of the University network were combined to form only origin/destination nodes if the coordinates of the origin and destination were the same in the CONTRAM input data.

In CONTRAM, it is not necessary to identify a link from the origin or to the destination. For example, the vehicles that begin their trip at an internal origin or finish their trip at an internal destination do not follow an explicit link from the origin or to the destination. The vehicles start or end their trip at the node on the network that is closest to that origin or destination. Similarly, vehicles exiting the network to an external destination do not use an explicit link and finish their trip at the node closest to their destination. However, vehicles that enter the network from external zones follow an explicit link and experience travel time and delay.

ASSIGN codes connections to zones somewhat differently. ASSIGN uses the concept of "dummy" links to connect the zones to the network. The dummy links do not add to the route possibilities because a travel time impedance is added to the generalized cost function in order to stop the vehicles from "shortcutting". In fact, "dummy" links are only used by vehicles that must enter or leave the network. "Dummy" links to and from the nodes were added to the University network and were coded as very short links with large saturation flows. The vehicles that used these links to leave their origins or to get to their destinations experienced very little travel time delay as they were attempting to get on or off the network due to the large saturation flows and short link lengths.

3.4 Validation of ASSIGN for the University Network

The final ASSIGN model network consists of 54 zones and 809 nodes. There are 1282 links that connect the nodes and zones where 296 links are uncontrolled, 221 links are stop controlled and 285 links are signalized. The remainder of the links are "dummy" links that connect the arterial and collector roadways to the zones.

The ASSIGN program is capable of determining link flows, link travel times, link fuel consumption, CO, HC, and NO levels and aggregate results based on three different types of algorithms: the convex combination; the method of successive averages; and the incremental assignment method. For validation purposes, traffic is routed based solely on minimizing travel time where the BPR function shown in Equation 2.1 is used in the assignment model. It is assumed that all links on the University network have the same travel time characteristics where the travel time increases linearly with flow (i.e. the parameters to the BPR function are $\alpha = 1$ and $\beta = 1$). It should be noted that a linear travel time relationship most accurately represents the CONTRAM specified speed flow relationship for under-saturated conditions.

Surveyed link flow data at several intersections provided from the City of Edmonton was the primary source of information used to validate the ASSIGN program. The surveyed (measured) link flow data and predicted ASSIGN link flows were compared based on a regression analysis as well as based on an evaluation method designed by the City of Edmonton. This evaluation method is described in section 3.4.1. Furthermore, the ASSIGN model results were compared with the CONTRAM output link flow statistics.

Measured link flow data was available for 25 of the 98 intersections in the University network. The intersection data provided by the City of Edmonton is a random sample whereby signalized, uncontrolled and stopped controlled intersections are used in the calibration of the University network. Modifications to the measured data were minimal: The measured traffic flows at the intersections were either increased or decreased by a growth rate of 2% in order to match the inputted O-D flow rates which represented the traffic demand for January 1993. Equation 3.2 shows the adjusted flow rates with respect to the difference between the base year (1993) and the survey year. The traffic flow counts at the intersections were available from the City of Edmonton where these counts were surveyed between 1992 and 1994.

$$f_a = f_a * 1.02^x \tag{3.2}$$

Where:

f_a = Link Flow
x = Difference between the base year and the survey year

The flows on the additional turning links (i.e. link numbers 3000 - 4000) in the ASSIGN network data files were combined with the flows of their original straight through link for comparison of the ASSIGN model results with the CONTRAM link flow output statistics. The combined link flows were also used for the validation of ASSIGN when the predicted link flows are compared with the measured (surveyed) data.

3.4.1 City of Edmonton Calibration Process

The City of Edmonton uses a goodness of fit criteria for calibrating the CONTRAM model. The goodness of fit test compares the actual measured volume with the link flow results from an assignment program. This test was adopted in the thesis to compare the ASSIGN link flow results with the measured link flow data.

Table 3.1 shows the absolute differences permitted when the results of the model link flows are compared with surveyed link flow data ranges within the city. These allowable absolute differences are placed in three possible categories: Good, acceptable and poor. If, for example, the difference in link volume between the measured and predicted results is small, the link would be assigned a value of one. Furthermore, if the difference in link volume between the actual and predicted results is acceptable, the link would be assigned a value of two and similarly, if the difference is large, a value of three would be assigned to the link. A value of three indicates that the predicted link flows are significantly different from the actual measured intersection flows.

From the information presented in Table 3.1, it is also possible to convert the absolute allowable differences of the predicted link flows into a percentage range. Table 3.2 illustrates the percentage differences allowed between the measured and predicted data at the "good" and "acceptable" category. As an example, if the actual volume at an intersection approach is 600 v/h and the predicted volume is 650 v/h, the difference between the measured and ASSIGN volume is 50 v/h or 9%. The goodness of fit table indicates that this difference falls within the "good" category where this link would then be assigned a value of one.

Table 3.1: Goodness of Fit Test

	Absolute Difference in Volume between the Measured and ASSIGN data		
Actual Volume	**Good**	**Acceptable**	**Poor**
< 300	90	91-150	>150
400	100	101-200	>200
500	125	126-250	>250
600	150	151-300	>300
700	175	176-350	>350
800	200	201-400	>400
1400	210	211-420	>420
1800	270	271-540	>540
2200	330	331-660	>660

Table 3.2: Allowable Percentage Ranges in the Goodness of Fit Test

	Allowable Percentage Ranges at the Good and Acceptable Level	
Volume	**Good**	**Acceptable**
<300	± 30%	± 30%-50%
400	± 25%	± 30%-50%
500	± 25%	± 30%-50%
600	± 25%	± 30%-50%
700	± 25%	± 30%-50%
800	± 25%	± 30%-50%
1400	± 15%	± 15%-30%
1800	± 15%	± 15%-30%
2200	± 15%	± 15%-30%

3.4.2 Regression Analysis

ASSIGN is validated based on the four different modelling methods discussed in section 3.3. These methods are:

1. "CONTRAM" method
2. "Short artery" method
3. "Long artery" method
4. "Combined" method

Each method is analyzed in order to determine the most suitable network for further analysis. The analysis is based on comparing the measured volume data (surveyed data) and the CONTRAM link flow data with the ASSIGN link flow results. First, however, the results of the CONTRAM data received by the City of Edmonton are compared with the available measured data and used as a reference for the following link modelling analysis.

The correlation between the CONTRAM link flow results for the University network and the measured data may be shown in Figure 3.7. In this example, Figure 3.7 shows some scatter between the measured and the CONTRAM results. It was also found that the R^2 value based on a least squares regression analysis is 0.93.

As already mentioned, the above analysis is used as a reference for the following sections where the four modelling methods used in ASSIGN are compared with the surveyed and CONTRAM data. It will be shown that the predicted link flows in ASSIGN are similar to the surveyed data and the CONTRAM data as the link connectivity methods become more complex.

"CONTRAM" Method

As already mentioned in section 3.3, the "CONTRAM" method implies that the ASSIGN network data files are converted directly from the CONTRAM network characteristic files. That is, turning links as well as straight through links for the same to-node could exist. Figure 3.3a shown earlier is a schematic diagram of the ASSIGN link connections that represent the CONTRAM format. This method, however, as already mentioned, is not appropriate for a node based system such as ASSIGN.

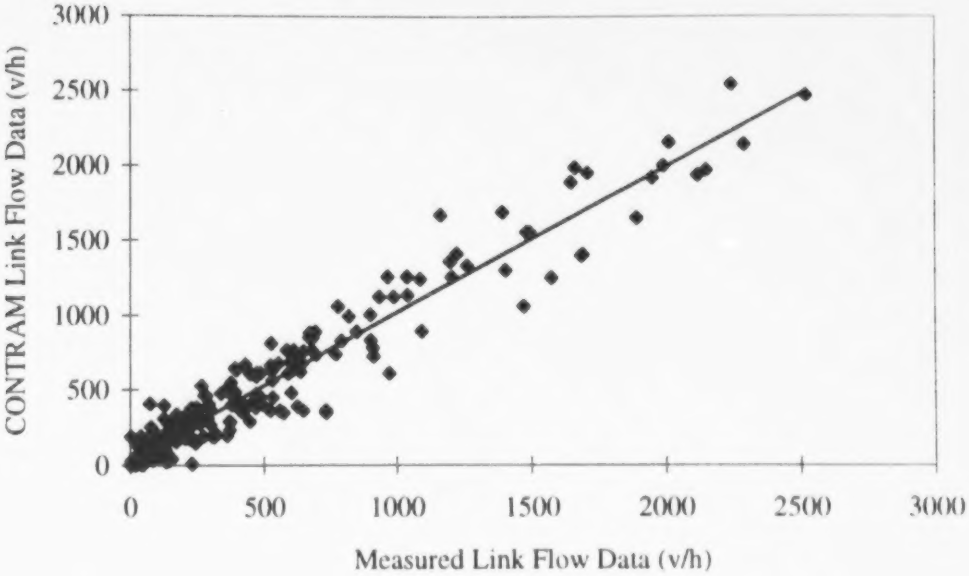


Figure 3.7 - Comparison of CONTRAM and the Measured Link Flow Data

The results of the regression analysis are illustrated in Figure 3.8 where the measured data is shown as the independent variable and the ASSIGN link flow data is shown as the dependent variable. The graph shows some scatter about the best fit regression line between the predicted and measured results.

Furthermore, Figure 3.9 shows a similar pattern when the ASSIGN link flow data is plotted against CONTRAM where in this case the CONTRAM link flows are the control group. The trend is linear, however, more scatter about the regression line exists between the two programs when the link connections are explicitly derived from CONTRAM than if the other coding methods such as the "long artery", the "short artery" or the "combined" method are used as shown in the following sections.

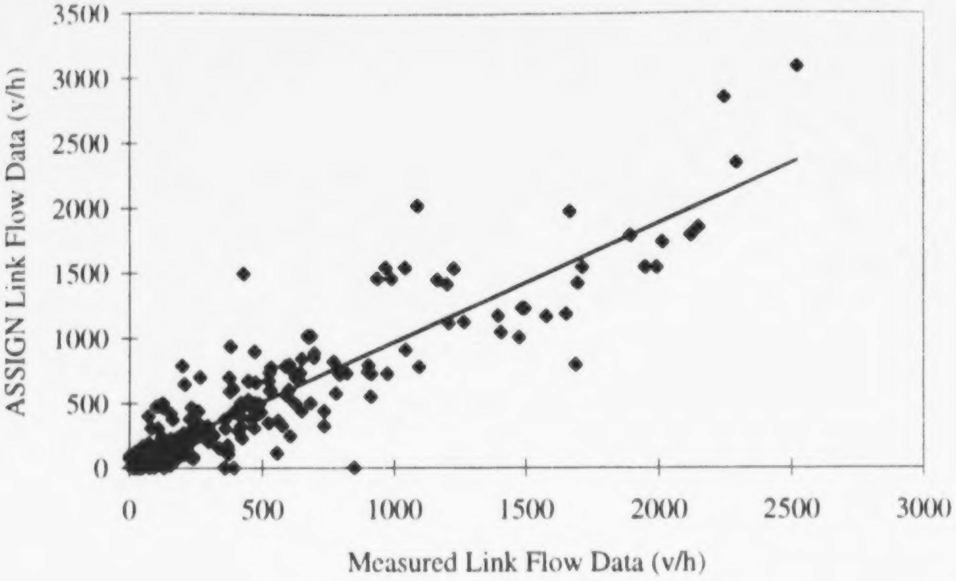


Figure 3.8 - Comparison of the Measured and ASSIGN Link Flow Data Based on the "CONTRAM" Method

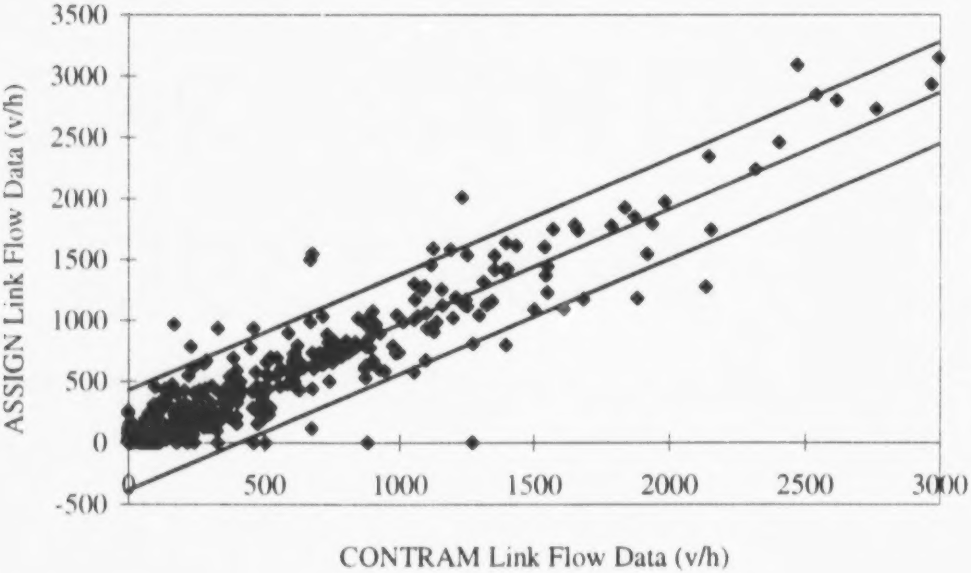


Figure 3.9 - Comparison of CONTRAM and ASSIGN based on the "CONTRAM" Method

In order to easily compare each link modelling method, a few key parameters are summarized in Table 3.3 for the "CONTRAM", "long artery", "short artery" and "combined" method described in ASSIGN. Table 3.3 shows the R^2 value, the standard error of the y estimate as well as the regression line parameters. The standard error of the y estimate may be interpreted as the sum of the squares of the deviation of y (SSE) where the best fit regression line is a minimum (Mendenhall and Sincich, 1992).

It is shown in the table that the R^2 value based on the "CONTRAM" method and the measured link flow data is 0.798. Similarly, the R^2 value when ASSIGN is compared with CONTRAM for the same network configuration is 0.869. It is also shown that the SSE values for a "CONTRAM" network configuration are the highest among all link connectivity methods when compared with the measured and CONTRAM data. These values further indicate scatter about the regression line between ASSIGN, CONTRAM and the measured data when the link characteristic files in CONTRAM are directly converted to an ASSIGN format. Furthermore, it is indicated from the table that the slope of the best fit regression line between ASSIGN and the surveyed data is 8.2 % lower where the reference is a line with a slope equal to one. Similarly, the slope of the line between ASSIGN and CONTRAM is 5.2 % lower.

"Short Artery" Method

It has already been mentioned in section 3.3 that in order to mimic a link based system, an 8-node coordinate system in ASSIGN was developed. This method ensured that the vehicles would use the appropriate lane when making turns at an intersection. Figure 3.10 illustrates the relationship between the ASSIGN and the measured link flow data for the "short artery" method. A much higher correlation exists between the predicted and measured data than from the previous "CONTRAM" example where the links were represented with only one node for the straight through and turning movements at the same intersection. This increase in correlation is shown by the fact that the most of the values fall within the 95% prediction limits illustrated in Figure 3.10.

Furthermore, there exists a significant improvement in the R^2 value which has changed from 0.798 in the original "CONTRAM" example to 0.885 in the "short artery" method. Moreover, it is also shown in Table 3.3 that the standard error of y estimate is lower and the slope of the line is very close to one.

The differences between the ASSIGN and the CONTRAM link flows also improved significantly as shown in Figure 3.11. It is indicated on the graph that most of the values of the actual predicted data fall within the 95% prediction limits. There are also some interesting trends found in the regression parameters between ASSIGN and CONTRAM based on a "short artery" method. The first is that the standard error of y estimates decreased to 150.8 from 206.8 in the "CONTRAM" example. Second, the intercept is negative and the slope of the line increased to a value greater than one.

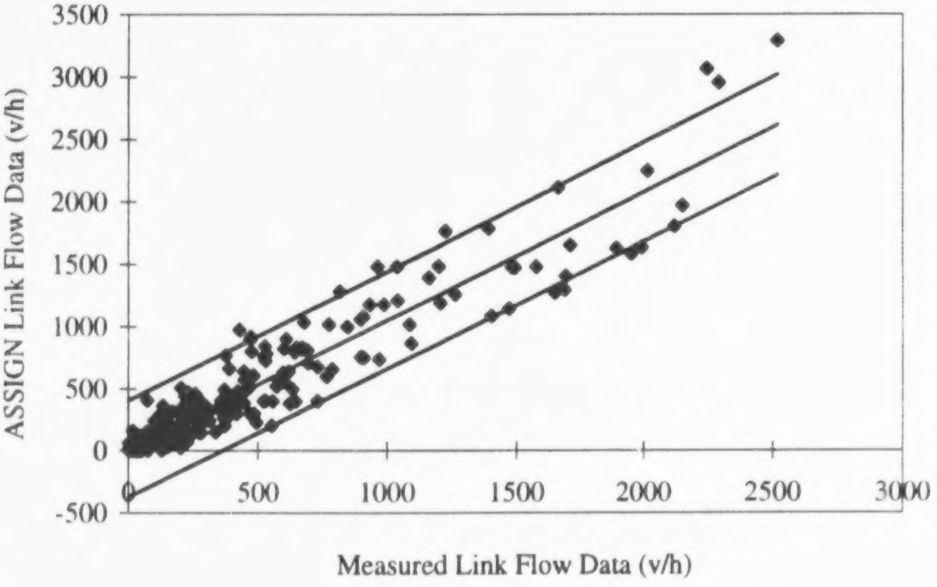


Figure 3.10 - Comparison of ASSIGN and Measured Link Flow Data Based on the "Short Artery" Method

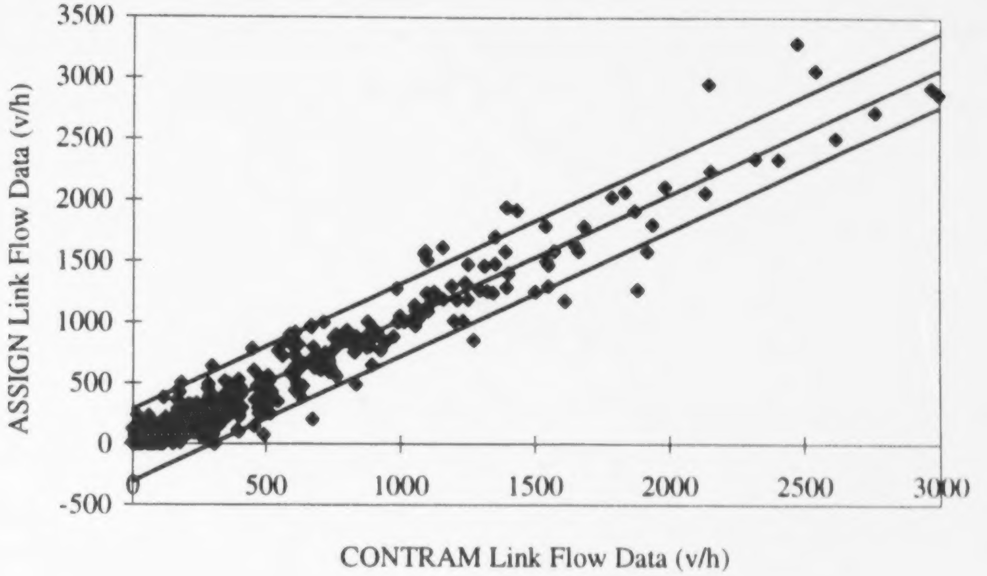


Figure 3.11 - Comparison of ASSIGN and CONTRAM Link Flow Data Based on the "Short Artery" Method

"Long Artery" Method

Figure 3.12 illustrates the relationship between the results of the ASSIGN model for the "long artery" method and the measured link flow data. It was found that less dispersion about the regression line exists if the intersections are modelled with short link lengths rather than modelling the intersections with long links (i.e. "short artery" method). In effect, vehicles are using slightly different routes due to the shorter delay time at the intersections. The major problem with this method is that signals at intersections have very little effect on the overall driver behaviour -- route choice as already mentioned in section 3.3.2.

The R^2 value for the "long artery" method also increased as indicated in Table 3.3 where an improvement of 3.8% exists when compared to the R^2 value from the previous "short artery" method. Furthermore, it is shown in Table 3.3 that the standard error of y estimate when compared against all the other methods is the lowest at 156.

Similarly, Figure 3.13 shows the relationship between the model results of CONTRAM and ASSIGN. The graph indicates a high correlation between ASSIGN and CONTRAM for links that are modelled by the "long artery" method because of the fact that the 95% confidence limits band is much tighter when compared to the same graph that represents the results of the "short artery" method. In this example, it was found that the R^2 value is the highest at 0.96 and that the standard error of estimates is the lowest at 115.6. Furthermore, Table 3.3 indicates that the intercept is close to zero and the slope of the line is close to one.

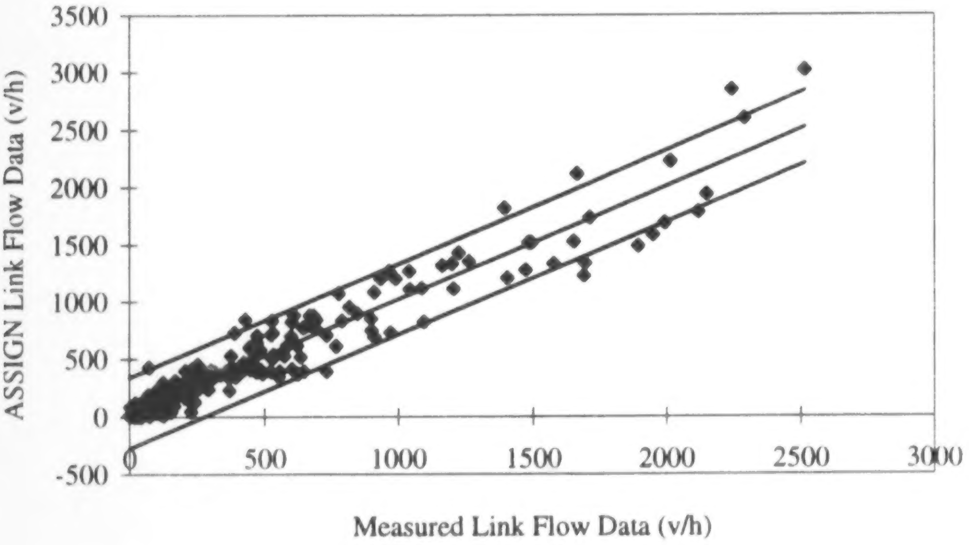


Figure 3.12 - Comparison of ASSIGN and Measured Link Flow Data Based on the "Long Artery" Method

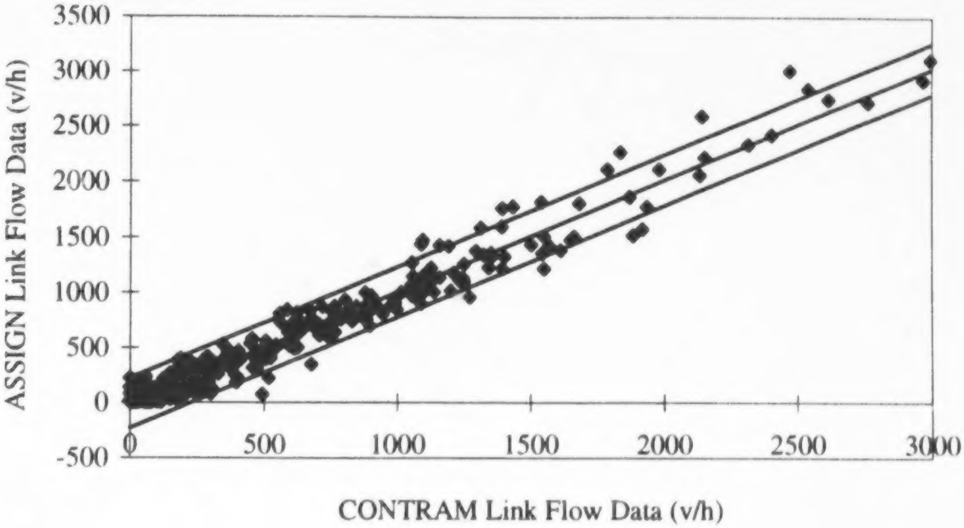


Figure 3.13 - Comparison of ASSIGN and CONTRAM Link Flow Data Based on the "Long Artery" Method

'Combined" Method

As already illustrated in section 3.3.4 the "combined" method is the most viable because both the "long artery" and "short artery" concepts are applied depending on the type of intersection. The final results indicated in Figure 3.14 show that the differences in link flows between ASSIGN and the measured data appear very similar to those from the "long artery" method. The R^2 value, equal to 0.916, based on the ASSIGN and measured data for the "combined" method is also very similar to the "long artery" method where the R^2 value is 0.919.

Furthermore, Figure 3.15 shows the results of the "combined" method and CONTRAM link flow data. It is indicated on the graph that the correlation in the link flow results between the "combined" method and CONTRAM is high and similar to the correlation as in the "long artery" method. The R^2 value between the best fit regression line and the predicted data is 0.958 as indicated in Table 3.3. It is also shown in the table that the slope of the line is close to one and that the difference in the standard error of the y estimate between the "long artery" and "combined" method is less than four. Even though, R^2 and the standard error of the y estimate indicates a better correlation between the measured and predicted data for the "long artery" method, the "combined" method is chosen for further work because of the theory behind this example. It is also chosen because of the fact that the slope of the line is closer to one than from the "long artery" method.

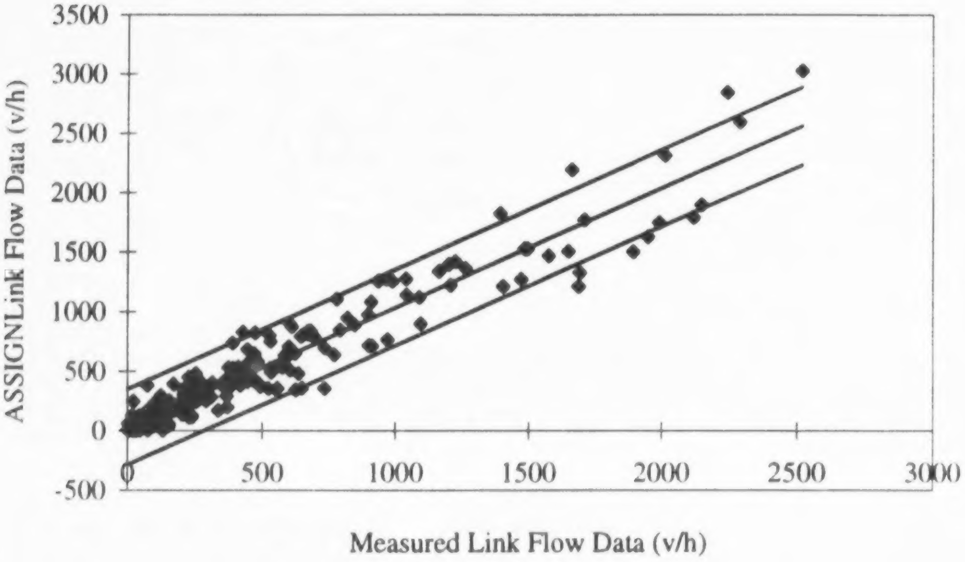
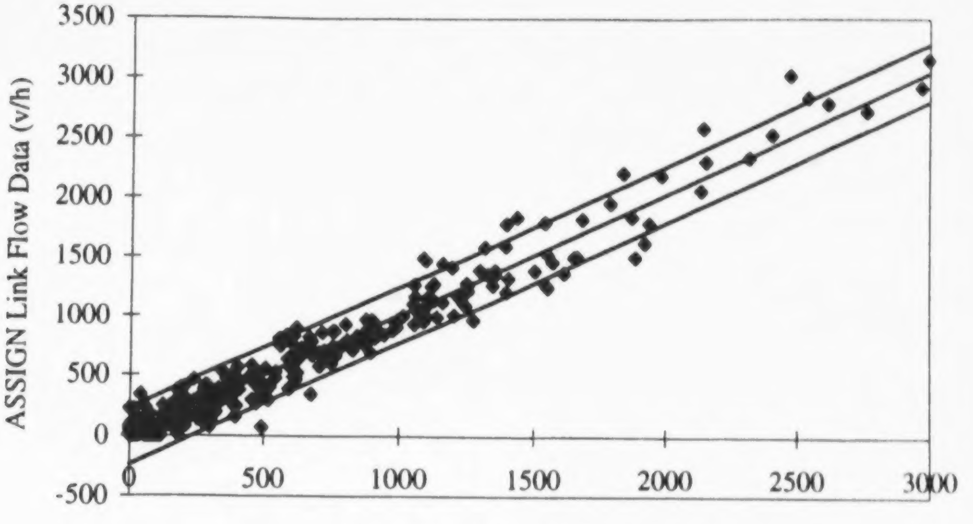


Figure 3.14 - Comparison of ASSIGN and Measured Link Flow Data Based on the "Combined" Method



CONTRAM Link Flow Data (v/h)

Figure 3.15 - Comparison of ASSIGN and CONTRAM Link Flow Data Based on the "Combined" Method

Table 3.3 Regression Parameters from the ASSIGN Model Runs

Descriptor	CONTRAM		"Short Artery"		"Long Artery"		"Combined"	
	*M	*C	M	C	M	C	M	C
R^2	.798	.869	.885	.936	.919	.96	.916	.958
Standard Error (SSE)	245.2	206.8	197.6	150.8	156.0	115.6	161.6	119.0
Intercept	49.57	18.2	11.17	-13.6	29.46	-5.5	29.05	-7.32
X Variable	.918	.948	1.033	1.031	.989	1.013	1.003	1.019

* M = Measured Data
C = CONTRAM Data

3.4.3 Goodness of Fit Analysis

Table 3.4 illustrates the number of links that fall within the "good", "acceptable" and "poor" category when the measured link flow data is compared with the CONTRAM output statistics and the ASSIGN link flow statistics. The table is divided into two parts. The first part illustrates the number of links placed in each category based on the CONTRAM output link flows and the measured link flow data. The second part compares the results of the ASSIGN data and measured data for the different link configurations discussed in the previous sections.

It was found from the goodness of fit test that if the ASSIGN link connections are directly interpreted from the CONTRAM files (i.e. "CONTRAM" method), the number of links in the poor category increases by 177% where the reference is the results of the goodness of fit analysis for the link flows generated from the CONTRAM program provided by the City of Edmonton. The number of acceptable links also decreases by 20% for this method.

The improvement in the correlation between the predicted least squares line and the actual data shown earlier for the "short artery" method is also indicated in the goodness of fit test. The number of poor links decreased from a value of 36 in the original "CONTRAM" method to a value of 28 for the "short artery" method. Similarly, the number of links placed in the "good" category increased by 19%.

If the University network is composed solely of long artery links and short intersection links (i.e. "long artery" method) or a combination of the two (i.e. "combined" method), then similar results as to the number of links in each category are found. The percentage difference in the number of links in each category is on the order of less than 9% for the "long artery" method and "combined" method. It is also indicated in the table that the results shown for the "combined" and "long artery" method are similar to the results of part 1. Furthermore, Table 3.4 shows that the "long artery" method, overall, generated better results even when compared to the original CONTRAM output statistics.

Table 3.4 - Goodness of Fit Analysis Summary

Program	Link Description	Good	Acceptable	Poor
CONTRAM	CONTRAM Output	138	53	13
ASSIGN	CONTRAM Method	111	57	36
	"Short Artery" Method	132	44	28
	"Long Artery" Method	144	49	11
	"Combined" Method	139	53	12

3.5 Conclusions

1. Proper network coding is necessary in order to realistically represent an urban network. Transportation engineers need to determine a method to realistically model link connections, saturation flows, link speeds, and turning movements. In many cases, simple coding configurations such as the one shown in Figure 3.3a may be feasible when analyzing long term aggregate problems for a large network at the strategic level. However, for short term traffic control analyses where smaller portions of a city is analyzed, a more detailed node/link system is required. The 8-node coordinate system is appropriate for modelling short term changes within a network when a node based system is used. Turning movements and flows within this system can be easily identified and analyzed.

2. It was found that there were four possible ways in which the University network could be modelled with the ASSIGN program. The first method was described as the CONTRAM method where the network characteristics files were directly converted from CONTRAM to ASSIGN. This method, however, generated a high dispersion about the best fit regression line when the link flow data between the survey counts and the ASSIGN model were compared. The other methods described in this chapter were referred to as the 8-node coordinate system where the link connection were divided into two link sets: Intersection and artery links. It was shown that the "short artery" method improved the correlation between ASSIGN, CONTRAM and the measured data. Based

on a regression analysis which compared ASSIGN with the surveyed data, the R^2 value increased from 0.798 in the "CONTRAM" method to 0.885 for the "short artery" method. It was also found that the "long artery" and "combined" method resulted in similar link flows when compared with the surveyed and CONTRAM data. The R^2 values in the regression analysis when compared with the surveyed data for the "long artery" and "combined" method were 0.916 and 0.919, respectively. Furthermore, it was found that the differences in the number of links in the "good", "acceptable" and "poor" category ranged on the order of less than 9% for both the "long artery" and "combined" method.

3. Based on the results of the regression and goodness of fit test, it was decided that the "combined" method will be used to model link connections for the University network. It was also shown that ASSIGN is a suitable model for further work into the area of routing traffic based on environmental objectives. This is due to the strong correlation between the link flow results of CONTRAM and ASSIGN. The ASSIGN model is also more appropriate for the research conducted in later chapters because the code is available and changes within the program such as adjusting the generalized cost functions are therefore possible.

Chapter 4 - Environmental Objectives in Traffic Assignment

4.0 Introduction

Historically the primary tools for reducing vehicular and traffic noise pollution have consisted of stricter noise and air pollution policies and regulations. These air pollution policies and regulations have resulted in quieter and cleaner vehicular engines. The recent advances in electronic toll collection systems and route guidance capabilities, have resulted in alternative methods of attaining reductions in traffic congestion and air pollution by directly or indirectly influencing driver route choice. This chapter examines the impact of using Intelligent Transportation Systems (ITS) to reduce the amount of air pollution by explicitly charging the drivers for the amount of pollution they produce or by routing the traffic such that the total amount of vehicular pollutants is minimized. While this is a hypothetical situation, the technology does exist and it is important to determine whether environmental objectives in traffic routing strategies will have any effect on the overall system costs and link flows.

This chapter is divided into three sections. First, environmental concepts in traffic assignment modelling are introduced. This is followed by a discussion on the problems with using the environmental cost components within the generalized cost functions for the traditional user equilibrium and system optimal assignment algorithms. In this section, the "environmental" marginal cost function used to define a system optimal assignment model is also derived. Second, "environmental" user equilibrium and system optimal traffic assignment principles are illustrated on a small two link network. Lastly, a user equilibrium and system optimal traffic assignment based on vehicular pollutants is performed on networks representing Ottawa and Edmonton. The total costs as well as the route costs directly affected by the closure of Keillor Road on the University network will be analyzed. Furthermore, the system costs are analyzed when the demand rate is varied on both the University and Ottawa network.

4.1 Environmental Concepts in Traffic Assignment Modelling

In the next few sections, it is assumed that the vehicles are assigned based solely on minimizing vehicular pollutants within an urban network. As an extreme example, the users are assigned on the network to minimize their own rate CO emissions because they are charged through electronic toll collection systems, on the amount of pollution they produce. Although, routing traffic based solely on minimizing CO emissions may be unrealistic, it allows transportation engineers to determine the changes in route flows and total pollutant emissions on a network that may occur if only environmental objectives are included in the traffic routing strategies that are implemented by ITS technologies.

An alternative example may be to use ITS technologies to minimize the total CO emissions produced by all the vehicles on the network. This objective could be achieved by explicitly routing the individual drivers through centralized route guidance systems. The traffic assignment could be modelled using SO objectives where the generalized cost is a function of CO emissions. Similar to the UE assignment that minimizes individual CO emissions, a SO assignment based solely on minimizing the total pollutant emissions is unrealistic. However, traffic engineers can use the results of the traffic assignment based on SO environmental objectives as reference to all the possible solutions.

In this thesis, three cases are presented which include, traffic assignment modelling based on minimizing fuel consumption, CO emissions, and HC emissions. Furthermore, Table 4.1 shows the key to the abbreviations used in the following sections and later chapters. For example, UE_TT refers to a user equilibrium assignment based on travel time

Table 4.1 - Key to Acronyms

UE_TT	User Equilibrium Traffic Assignment Based on Travel Time
SO_TT	System Optimal Traffic Assignment Based on Travel Time
UE_F	User Equilibrium Traffic Assignment Based on Fuel Consumption
SO_F	System Optimal Traffic Assignment Based on Fuel Consumption
UE_CO	User Equilibrium Traffic Assignment Based on Carbon Monoxide Emissions
SO_CO	System Optimal Traffic Assignment Based on Carbon Monoxide Emissions
UE_HC	User Equilibrium Traffic Assignment Based on Hydrocarbon Emissions
SO_HC	System Optimal Traffic Assignment Based on Hydrocarbon Emissions

4.1.1 Problems with Environmental Components in the User Generalized Cost Function

Development of an appropriate generalized cost function based on the environment is problematic. There has been little research on identifying the appropriate factors that would include the environment in traffic assignment modelling. The Frank-Wolfe algorithm used to solve traffic assignment problems produces a unique and stable solution when the function is convex (Sheffi, 1985). For example, the BPR function illustrated in Equation 2.1 increases monotonically with volume. This function is entirely convex and therefore the Frank-Wolfe algorithm can be used to determine an optimal equilibrium solution. Most environmental cost functions, however, are not monotonically increasing with flow and therefore do not lend themselves to the criteria for a unique and stable solution. The Frank-Wolfe algorithm could be used to solve the assignment based on minimizing noise or air pollution but the algorithm will not guarantee a solution with a global optimum.

In this thesis, vehicle emission rates are calculated based on the TRANSYT -7F average speed model which is shown in Equation 2.24a. It is assumed that the vehicles travel at a constant rate throughout their journey and the grades on the roadways are 0%. Table 4.2 lists the pollutants examined in this chapter along with the recommended values of the constants A, B, and C in Equation 2.24a (Penic and Upchurch, 1992).

Table 4.2 Parameters in Pollution Emission Assignment Analysis

Parameter	A	B	C
Fuel Consumption	14.234	0.020016	100000
Carbon Monoxide (CO)	3.3963	0.014561	1000
Hydrocarbon (HC)	2.7843	0.023544	10000

Fuel consumption and the vehicle emission functions from the TRANSYT-7F model are illustrated in Figure 4.1 and 4.2 where the rate of production is shown as a function of average speed. The average speed for this particular example is taken from an example problem where the travel time and related average speed on a link is derived from the BPR function shown in Equation 2.1 with $\alpha = 0.15$ and $\beta = 4$. The fuel consumption and CO emission curves are similar where the pollutant rate decreases to a minimum at a certain travel speed and then increases again. HC emissions, however, always increase with respect to speed for this particular example while NO emissions decreases as the speed reaches 90 km/h.

As already mentioned, one of the key problems with using fuel consumption or pollutant emission generalized cost functions is that fact that these functions are not convex with respect to flow. This is shown graphically in Figure 4.3 for the same example. It is illustrated on the graph that the NO emission function with respect to flow is concave and that the HC emissions always increase with flow. Because of the concave nature of the NO emission function, it will not be used in further analysis. Furthermore, it is shown in the graph that the fuel consumption and CO emissions curves are concave up to approximately 5000 v/h. At a link flow of 5000 v/h, a point of inflection changes the slope of the curve where the derivative of the function becomes positive (i.e. the function is convex).

The volume to capacity ratio at the point of inflection may be determined by taking the derivative of the cost function and setting the derivative equal to zero. The critical volume and related critical speed may then be calculated for this v/c ratio. When the average speed is less than the critical speed, the function is convex. For example, it was found that for CO emissions, the critical speed for any volume to capacity ratio is 75.35 km/h. Therefore, it may be assumed that the convex combinations algorithm will find the optimal solution for any network that have average speeds less than 75.35 km/h. Similarly, the critical speed for fuel consumption rates has been identified as 65.4 km/h for any link on the network. In the case of the University network, all free flow travel speeds are less than the critical value of 75.35 km/h and therefore the convex combinations algorithm is valid for determining CO emissions based on a user equilibrium assignment. In the case for fuel consumption, all average speeds on the University network are also less than 65.4 km/h and therefore, it is also possible to use the convex combinations to route traffic based on minimizing fuel consumption rates.

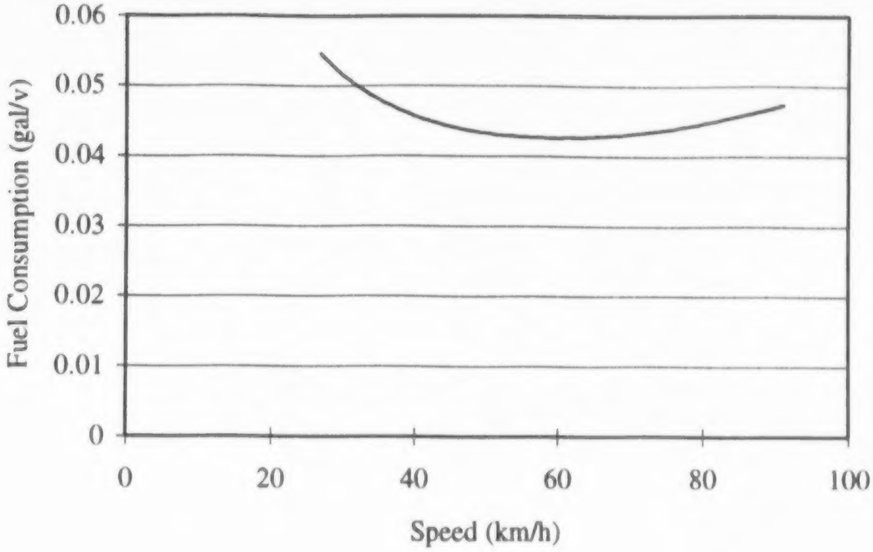


Figure 4.1 - Fuel Consumption Rate vs. Speed

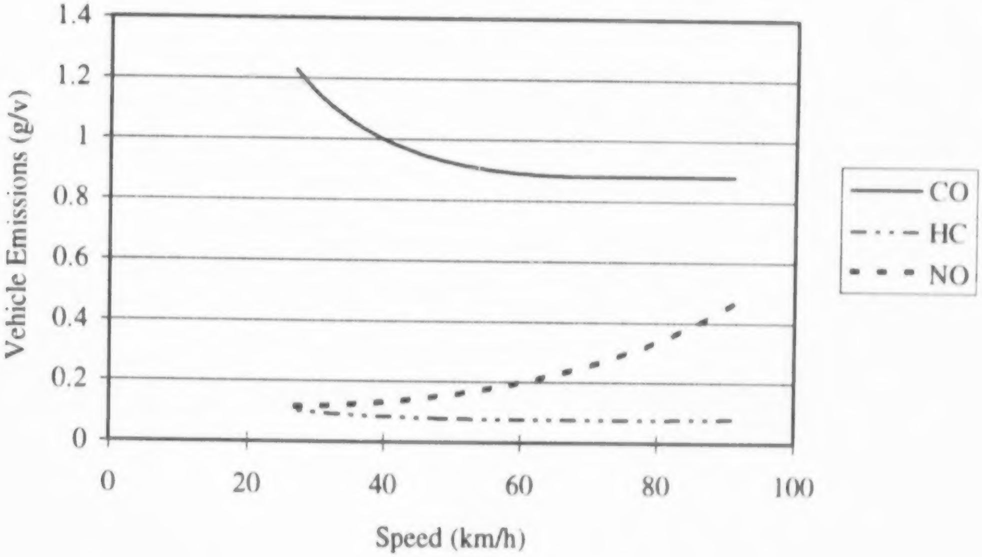


Figure 4.2 - Pollutant Emission Rate vs. Speed

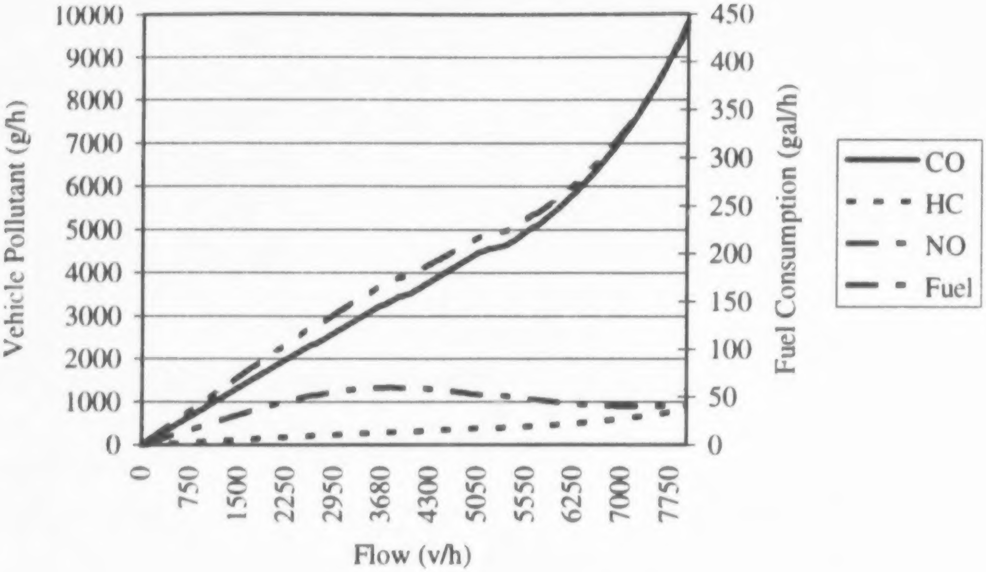


Figure 4.3 - Vehicle Pollutants vs. Flow

4.1.2 Determining the Marginal Cost Function for a System Optimal assignment Based on Environmental Objectives

The traditional objective of a system optimal assignment is to determine the route flows such that the travel time for the entire system is a minimum. This is accomplished by ensuring that the marginal travel time on all routes is equal (Sheffi, 1985). The marginal cost function for a route is the derivative of the total travel time for all the vehicles on a particular link with respect to flow on the link as shown in Equation 4.1a. Although the intermediate steps are not shown in the text, it is proven that the derivative of the travel time function may be separated into two separate sections as shown in Equation 4.1b. The first part represents the travel time contribution of an additional user on link a. The second part represents the additional travel time burden that the user inflicts on all the other users already on link a (Sheffi, 1985).

$$T_a(V_a) = \frac{d(t_a(V_a)V_a)}{dV_a} \tag{4.1a}$$

or

$$T_a(V_a)= t_a(V_a)+\frac{V_a dt_a(V_a)}{dV_a} \tag{4.1b}$$

Where:

$T_a(V_a)$ = Marginal travel time on link a as a function of flow
V_a = Flow on link a
t_a = Travel time on link a

If the BPR function shown in Equation 2.1 is substituted into Equation 4.1b, the marginal travel time is shown in Equation 4.2.

$$T(V_a)= fft_a(1+\alpha_a(\frac{V_a}{c_a})^{\beta_a}+(\beta_a fft_a \alpha_a V_a^{(\beta_a-1)}(\frac{1}{c_a})^{\beta_a})V_a \tag{4.2}$$

Where:

c_a = Capacity on link a
fft_a = Free flow link travel time
$\alpha_a \beta_a$ = BPR constants

For traffic assignment models that route the vehicles based on system optimal principles and environmental objectives, the marginal cost function for the chosen environmental conditions on all the links must also be equal. The total cost on the link is represented by the rate of production of pollutant per vehicle times the number of vehicles on the particular link. This is illustrated in Equation 4.3 where the total rate of pollutants is derived from the TRANSYT -7F rate of production model.

$$Total\ rop_a = \frac{ae^{bv_a}}{cv_a} d_a V_a \tag{4.3}$$

Where:

rop_a = Rate of production on link a (grams/hour or gallons/hour)
v_a = Average vehicular velocity on link a
d_a = Link length
a,b,c = Constants

Therefore the marginal cost function for the vehicular pollutants is the derivative of the function illustrated in Equation 4.3. This is shown in Equation 4.4a. The final solution of the marginal generalized cost function for fuel consumption and pollutant emissions is shown in Equation 4.4b.

$$ROP_a = \frac{d}{dV_a}\left(\frac{ae^{bv_a}}{cv_a} d_a V_a\right) \tag{4.4a}$$

$$ROP_a = e^{bv_a} \frac{a}{c}((fft_a \alpha_a \beta_a (\frac{V_a}{c_a}))(1 - bv_a) + fft_a(1 + \alpha_a (\frac{V_a}{c_a})^{\beta_a})) \tag{4.4b}$$

Where:

ROP_a = Marginal rate of production on link a

Similar to the user generalized cost function for vehicular pollutants, the marginal rate of production is not a convex function and the use of the convex combinations algorithm will not guarantee an optimal solution. However, it is also possible to identify the point of inflection where the derivative of the function is always positive. The point is identified by taking the derivative of the marginal cost function and determining the volume when the derivative is zero. However, the derivative of the marginal rate of production shown in Equation 4.4 does not lead to a simple equation where the volume may be isolated. Therefore, in this thesis, a numerical search was used to determine the critical volume to capacity ratio and critical speed for each link on the University network. It was found that the average speeds on the network for all links were below the critical speeds and therefore, the convex combinations algorithm could also be used to determine route flows and costs on the network based on a SO assignment.

4.2 Traffic Assignment Analysis for the Simple Two Link Network

The two link network consists of two nodes and two links and is shown in Figure 4.4. The O-D demand from node 1 to node 2 is 8000 v/h. There are two potential routes for these vehicles. The first route (link 1) is a two lane freeway that is 2000 metres long with a free flow travel speed of 100 km/h and a capacity of 2000 v/h/lane. The second route (link 2) is a shorter two lane arterial roadway that is 1000 metres long with a free flow travel speed of 60 km/h and capacity of 2000 v/h/lane.

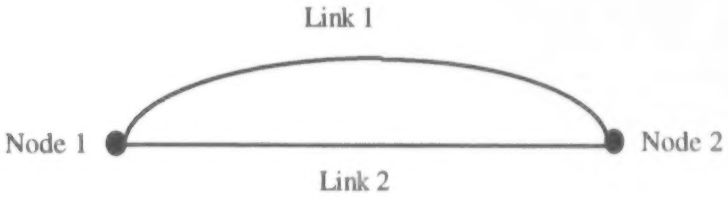


Figure 4.4 - Sample Network

The principles of the UE and SO traffic assignment model are first illustrated on a two link network, shown in Figure 4.4, where the objective is to minimize either the individual user travel time or the total system travel time on the network. Then, the impact on the link and overall system costs is examined when environmental objectives are used in the traffic assignment model. Figure 4.5 shows the travel time on both routes as a function of the flow on route 1. The UE solution is graphically defined as the point where the route travel times for the O-D pair cross. This is illustrated as point a in Figure 4.5 where the flow on route 1 is 5090 v/h and the flow on route 2 is 2910 v/h with a travel time on both routes equal to 100 seconds. These equilibrium link flows result in a total system travel time on the network of 223 veh-hours.

For a SO assignment where the vehicles on the network are assigned such that the total system travel time on the network is minimized, the flow on route 1 is increased to 5218 v/h and the flow on route 2 is reduced to 2782 v/h. This leads to a total system travel time of 222 veh-hours and it is shown as point b on the graph. The route flows, route travel times and system travel time for the UE and SO assignment are summarized in Table 4.3. The relative closeness of the UE and SO solutions is not solely due to the simplicity of the network because similar trends in the solution of the UE and SO assignments have been found for larger networks described in the literature (Sheffi, 1985).

Table 4.3 Assignment Based on Travel Time

Type	Route	Volume (v/h)	Travel Time (s)	Total (veh-hours)
SO	1	5218	103.3	222.0
	2	2782	93.7	
UE	1	5090	100.3	223.0
	2	2910	100.3	

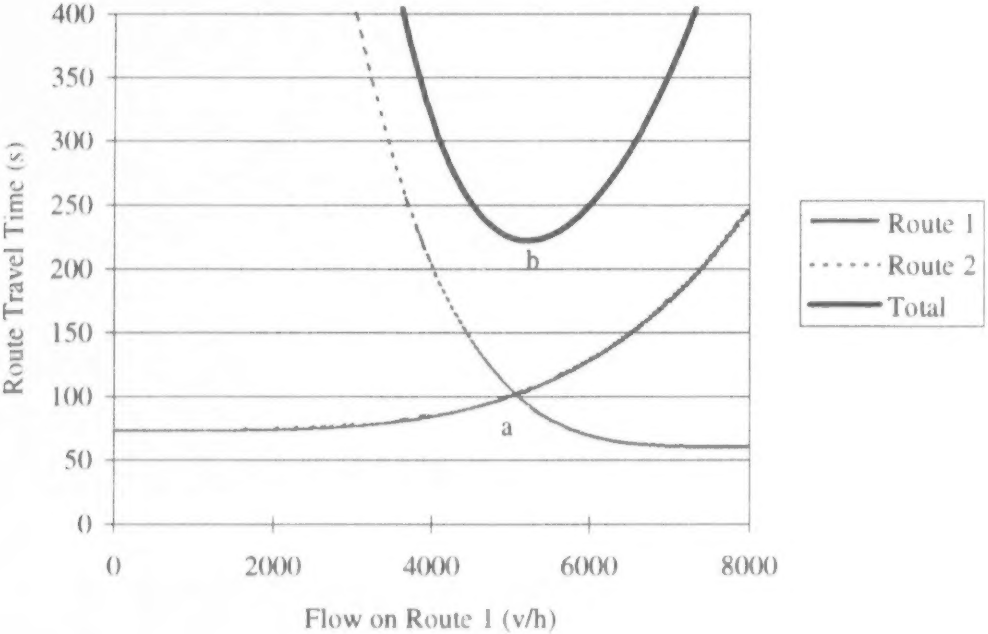


Figure 4.5 - Route Travel Time vs. Flow on Route 1

Table 4.4 illustrates the results of the UE and SO assignment based on fuel consumption. If a route guidance system is used to route traffic such that the total fuel consumption (SO_F) on the network is minimized than the difference in the link flow pattern when compared to a UE_TT is 0.65%. The rate of fuel consumed on route 2 based on an SO_F assignment is approximately 43% lower than the rate of fuel consumption experienced on route 1. It is also shown in Table 4.3 that if the drivers minimized their own rate of fuel consumption (UE assignment), the link travel time on route 2 is approximately 153% higher than if the drivers minimized their own travel time.

Table 4.4 Assignment Based on Fuel Consumption

Type	Route	Volume (v/h)	Rate (gal/v)	Travel Time (s)	Total (kg)
SO_F	1	5194	0.0427	102	289.5
	2	2806	0.0241	95	
UE_F	1	3680	0.0451	79	361.2
	2	4320	0.0451	256	

Table 4.5 lists the results of the assignment based on CO emissions. If the drivers were routed from a centralized route guidance system to achieve a SO_CO assignment, the rate of CO emissions is approximately 40% higher on route 1 when compared to the rate of CO emissions on route 2. Furthermore, the difference in route flows from the UE_TT and SO_CO is on the order of 1%. Therefore, for this simple example, the UE solution based on travel time is roughly equivalent to a SO assignment based strictly on minimizing CO emission levels. This pattern was also found in the previous example where the results were based on an assignment that minimized fuel consumption. This implies that allowing drivers to route themselves to minimize their own travel time would be the same as if a route guidance system was implemented with the objective of minimizing the total pollutant emissions.

A similar pattern in the route travel times as with the assignment based on minimizing user fuel consumption is found when drivers minimize their own rate of CO emissions. It is found that the link travel time on route 2 is significantly (i.e. 109%) higher than if the drivers were to minimize their own link travel times. Therefore, unless the drivers are explicitly assigned to the network or they are charged based on the amount of CO produced, the resulting solution is unstable because the drivers would be unwilling to increase their travel time in order to improve the CO emissions on the network.

Table 4.5 Assignment Based on CO Emissions

Type	Route	Volume (v/h)	Rate (g/v)	Travel Time (s)	Total (g)
SO_CO	1	5161	0.8839	102	6.09
	2	2840	0.5378	96.5	
UE_CO	1	3966	0.8922	82	7.14
	2	4034	0.8922	209	

Furthermore, Table 4.6 illustrates the results of an assignment based on HC emissions. A similar pattern in the route flows for a SO assignment is found as in the previous two examples. That is, the difference in route flows between the SO_HC and the UE_TT assignment for the same network is on the order of less than 1%.

Similarly, if the assignment is based on system objectives that minimizes the total HC emissions on the network, the link travel times on route 2 is significantly higher than the travel time on route 1.

In general, the results from the traffic assignment for the different objectives are very similar. The relative closeness of these results are not surprising given that the equations are from the same source and there is a high correlation between fuel consumption and the pollutants emissions.

Table 4.6 Assignment Based on HC Emissions

Type	Route	Volume (v/h)	Rate (g/v)	Travel Time (s)	Total (g)
SO_HC	1	5166	0.0748	102	0.514
	2	2834	0.0448	96.3	
UE_HC	1	3904	0.0762	82	0.61
	2	4096	0.0762	218	

Table 4.7 compares the total system costs for each objective considered in the traffic assignment model. The table shows the values of the total system travel time and

total fuel consumption, CO and HC emissions based on different objectives for the UE and SO assignment. The percentages indicated under each value in the table are the percentage difference in cost for each assignment objective where a SO assignment for the given condition at the left hand side of the table is the reference point. For example, the percentage difference in total travel time on the network between the UE and SO solutions that minimizes link travel times is on the order of 0.4% given that the reference condition is a SO_TT assignment. Similarly, it is found that there is a 75% increase in travel time when the system travel times are compared with the UE_F assignment.

The table also illustrates that the differences in the total travel time, fuel consumption, CO and HC emissions for a SO assignment based on the different objectives is on the order of less than 0.22%. This implies that the route flows are very similar given any system optimal assignment objective. Therefore, implementing a route guidance system to minimize the total travel time on the network is similar to using the same route guidance system to minimize the total pollutant emissions.

However, a user equilibrium assignment shows some trends that may at first appear to be counter-intuitive. For example, a UE_CO assignment generates higher CO emission levels than if the drivers are routed on the basis of a UE_TT assignment. A similar trend is shown if the objective is to charge the drivers for the amount of fuel or HC emissions they produce (i.e. UE assignment based on fuel or HC emissions). The total fuel consumed is actually the highest when drivers minimized their own rate of fuel consumption. Moreover, if the drivers were to minimize their own CO or HC emissions, the total fuel consumption would actually be less than from a UE_F assignment. The results of the UE assignment for environmental conditions implies that charging the drivers based on the amount of pollutant they emit may actually generate higher pollution levels on the network than if the drivers routed themselves to minimize their own travel time. It is also implied in the example, that minimizing CO or HC emissions generates better fuel consumption results on the part of the drivers than if the drivers minimized their own fuel consumption rate.

Table 4.7 - Comparison of System Costs Based on Different Traffic Assignment Objectives

		Traffic Assignment Objective			
		TT	FUEL	CO	HC
Total System Travel Time (veh-hours)	UE	222.94 (0.4%)	388.61 (75%)	325.16 (46.4%)	336.92 (51.6%)
	SO	222.1 (Base)	222.12 (0.009%)	222.27 (0.08%)	222.24 (0.06%)
Total Fuel Consumption (gal/h)	UE	289.73 (0.008%)	361.28 (25%)	333.17 (15%)	338.33 (18%)
	SO	289.52 (0%)	289.5 (Base)	289.53 (0%)	289.52 (0%)
Total CO Emissions (kg/h)	UE	6.09 (0.03%)	7.83 (29%)	7.14 (17%)	7.27 (19%)
	SO	6.09 (0.03%)	6.089 (0%)	6.088 (Base)	6.102 (0.22%)
Total HC Emissions (g/h)	UE	513.8 (0.06%)	655.6 (28%)	599.4 (17%)	609.7 (19%)
	SO	513.7 (0.04%)	513.6 (0.02%)	513.6 (0.02%)	513.5 (Base)

4.3 Application of Environmental Objectives for the University Network and the Ottawa Network

The analysis of the environmental objectives for the University network is divided into four sections. First, the total system travel time, fuel consumption, CO and HC emissions are compared at an aggregate level for the present 1993 O-D demand. The differences in pollutant emissions and total system travel time are identified from a UE and SO perspective and compared with respect to different traffic assignment objectives.

Second, the total pollution levels on 114 Street and Keillor Road are compared at a disaggregate level when Keillor Road is open and closed. For example, the differences in CO emissions on 114 Street are compared when drivers are routed explicitly by a route guidance system (SO assignment for different objectives) and when drivers route themselves to minimize their own generalized cost (UE assignment).

Third, a sensitivity analysis on the environmental impact on the University network is summarized when Keillor Road is open. In this section, the difference in flow, travel time, and CO emissions are compared on a link basis for a UE_TT assignment. The link costs have been identified when Keillor Road is open and closed for links that represent 114th street and Keillor Road.

Finally, the relationship between the total system costs and O-D demand rate are analyzed for two large networks. The networks used for this analysis are the Ottawa, Ontario network and Edmonton's University network. The Ottawa network represents a larger urban area with high speed arterial roadways and freeways whereas the University network illustrates a section of a large urban area with low arterial speeds. A description of the Ottawa network is found in section 4.3.4. The demand rates indicate variations in the total number of trips on the network and they are related to the weighted average volume to capacity ratio.

4.3.1 Analysis of the aggregate Costs for the University Network at the Current 1993 Demand Level

Table 4.8 illustrates the changes in total system travel time, fuel consumption, CO emissions and HC emissions when different generalized cost functions are used in the traffic assignment model to route traffic on the University network. The generalized cost functions are the same as those used in the simple two link network which include the BPR function for travel time and TRANSYT-7F functions for fuel consumption, CO and HC emissions. Also indicated in the table is the average percentage increase in system costs when drivers do not have access to Keillor Road.

If the drivers route themselves to minimize their own travel time or pollution levels, the differences in the total system travel time is less than 1% given any assignment objective. Although, the difference in total travel time on the network may seem small, it has been recorded in literature that improvements to system components with ITS technologies are on the order of less than 7% (King and Mast, 1990). For example, it is indicated in the table that the difference in travel time between a UE_TT and a UE_CO assignment is 0.4%. The largest difference is found when drivers minimize their own rate of fuel consumption where the increase in travel time is on the order of 0.74%. It is also shown that minimizing fuel consumption from a user point of view generates the highest overall link travel times when Keillor Road is closed.

Similarly, if route guidance technologies are used to route the traffic such that the total travel time or pollution levels are minimized, the effect on the total travel time on the network is similar for any objective. This is clearly indicated in the table: Given the same network, the total travel time differences are less than 0.56%. However, closing Keillor Road, results in an average increase in travel time of 2.9 %.

The changes in total fuel consumption, CO and HC emissions when different traffic assignment objectives are integrated into the model results in similar trends in the total production rate of pollutants as in the trends that were found for the total travel time on the network. The increase in total fuel consumption based on a UE_F assignment is on the order of 0.15% when compared to a UE_CO assignment. This implies that charging the drivers for the amount of fuel they consume will actually increase the total fuel consumption on the network. Moreover, if the drivers minimize their own rate of CO or HC emissions or if they are given explicit routes to generate system benefits, the differences in the routing of traffic based on different objectives are small (i.e. less than 1%) for both networks regardless of whether Keillor Road is opened or closed. However, there is approximately a 2% decrease in fuel consumption, CO, and HC emissions when Keillor Road is open.

The small differences in pollutant emissions and fuel consumption based on the different traffic assignment objectives implies that using route guidance technologies to achieve a system objective such as reducing the total pollution levels on the network would be the same as implementing a route guidance system with the objective of reducing link travel times and thus congestion. However, the small variations in system costs based on different objectives are due to the fact that the network represents only a section of a larger metropolitan area and thus route options are limited. Furthermore, the network is relatively uncongested and therefore due to the small travel time delay on the arterial roadways, the impact on the total pollutants and fuel consumption within the network is also small.

Table 4.8 - System Costs Based on Different Traffic Assignment Objectives

			Traffic Assignment Objective			
			TT	Fuel	CO	HC
Total Travel Time (veh-hours)	Keillor Closed	UE	2325.4	2342.7	2334.8	2337.2
		SO	2319.7	2323.8	2320.8	2321.8
	Keillor Open	UE	2260.3	2273.1	2266.1	2268.4
		SO	2254.9	2257.9	2256.2	2256.8
	% Increase		2.88%	3.06%	3.03%	3.03%
Fuel Consumption (gal/h)	Keillor Closed	UE	2046.2	2046.1	2044.0	2044.5
		SO	2045.6	2042.0	2042.0	2042.0
	Keillor Open	UE	2006.7	2004.7	2003.1	2003.4
		SO	2005.4	2001.7	2001.4	2001.5
	% Increase		1.97%	2.07%	2.04%	2.05%
CO Emissions (kg/h)	Keillor Closed	UE	45.41	45.45	45.39	45.41
		SO	45.38	45.32	45.31	45.31
	Keillor Open	UE	44.48	44.47	44.42	44.44
		SO	44.44	44.38	44.37	44.37
	% Increase		2.09%	2.20%	2.18%	2.18%
HC Emissions (g/h)	Keillor Closed	UE	3784.1	3786.5	3781.9	3783.1
		SO	3786.1	3776.7	3775.6	3775.8
	Keillor Open	UE	3707.8	3706.4	3702.5	3703.4
		SO	3704.6	3698.8	3698.1	3698.4
	% Increase	UE	2.06%	2.16%	2.14%	2.15%

4.3.2. Route Analysis

The following analysis is at a more disaggregate level where the fuel consumption, CO and HC emissions on the routes directly affected by the closure of Keillor Road (i.e. 114 Street and Saskatchewan Drive) are compared when Keillor Road is open and closed. Figure 4.6 is a schematic diagram of 114 Street which shows the intersections and the location of Keillor Road relative to 114 Street. It should also be noted that the overall distance along 114 Street from 72 Avenue to 87 Ave. is 8.1 km and the vehicle-km travel along Keillor Road is 8.6 km. Because the difference in the distances along the two corridors is small, environmental conditions may be compared. The sum of the fuel consumption, CO and HC emissions is determined by summing the total fuel consumed or pollutants emitted for each link along the corridor.

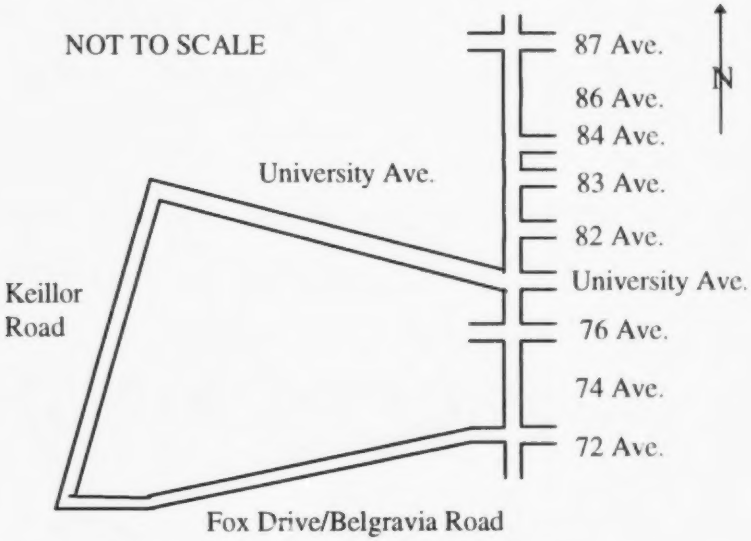


Figure 4.6 - 114 Street and Keillor Road Corridor

Table 4.9 illustrates the total pollutant costs on 114 Street when Keillor Road is opened and closed. It is illustrated in the table that the average fuel consumed per hour before the closure of Keillor Road is 130 gal/h. Similarly, the average CO and HC emissions are 2900 g/h and 240 g/h, respectively. When drivers do not have access to

Keillor Road, fuel consumption on an hourly basis increases to 150 gal/h on 114 Street. The CO and HC emissions also increase to an average rate of 3450 g/h and 295 g/h over all the objectives. The increase in fuel consumption on 114 Street is found to be equivalent to 42 vehicles idling for one hour given that the idling vehicles emit a constant rate of pollution as shown in Equation 2.24c in Chapter 2. Similarly, the increase in HC and CO emissions is equivalent to five vehicles idling for one hour.

Table 4.9 also illustrates the percentage increase in the vehicular pollutants based on the SO and UE assignment for the different objectives on 114 Street when Keillor Road is closed. It is found that the total fuel consumption, CO and HC production on 114 Street are higher for users that minimize their own rate of production (UE assignment) than if the drivers were explicitly routed to minimize the pollution levels (SO assignment). If, for example, the drivers minimize their own travel time (UE_TT), the average percentage increase in pollution on 114 Street in the lowest at approximately 18%. Furthermore, if the assignment is based on a UE_F then, the vehicles on 114 Street would generate the highest CO and HC emissions when Keillor Road is closed. The average increase in fuel consumption, CO and HC emissions when the objective is to ensure that the drivers minimize their own fuel production rate is approximately 23%. The high increase in fuel consumption when Keillor Road is closed implies that charging drivers for the amount of fuel they consume will actually increase the number of vehicles and thus other pollutants on 114 Street.

The percentage increase in pollutants on 114 Street by the closure of Keillor Road is the lowest if the drivers are assigned by a centralized route guidance system with the objective of reducing the total travel time on the network (i.e. SO_TT objective). It is also shown in the table that the pollutant emissions on 114 Street are higher if the drivers are explicitly routed to minimize the total pollutants as shown by the increasing trend in the percentage increase in pollution levels when compared to a SO_TT assignment. However, the overall increase in pollution levels on 114 Street from SO objectives is less than if the drivers minimize their own generalized cost (i.e. UE assignment). This implies that before and after the road closure, the amount of traffic routed to Keillor

Road/Saskatchewan Drive from a centralized route guidance system is higher than if drivers choose their own routes.

Table 4.9 - Total Environmental Costs on 114 Street When Keillor Road is Open and Closed

			Traffic Assignment Objective			
			TT	Fuel	CO	HC
Fuel Consumed (gal/h)	Keillor Closed	UE	158.7	165	160.2	159.8
		SO	144.2	145	145.3	145.1
	Keillor Open	UE	134.8	134.6	133.8	132.8
		SO	123.6	122.5	124.4	121.1
	% Increase	UE	17.7%	22.6%	19.8%	20.3%
		SO	16.7%	18.4%	16.8%	19.8%
CO Emissions (kg/h)	Keillor Closed	UE	3.57	3.72	3.61	3.60
		SO	3.24	3.26	3.27	3.26
	Keillor Open	UE	3.02	3.02	3.03	2.98
		SO	2.76	2.74	2.79	2.71
	% Increase	UE	18.2%	23.2%	20.2%	20.8%
		SO	17.1%	18.8%	17.2%	20.3%
HC Emissions (g/h)	Keillor Closed	UE	296.8	308.9	299.8	299
		SO	269.3	270.8	271.4	271.1
	Keillor Open	UE	251.4	250.9	249.6	247.7
		SO	230.1	228.2	231.7	225.6
	% Increase	UE	18.1%	23.1%	20.1%	20.7%
		SO	17.0%	18.7%	17.1%	20.1%

Increases in fuel consumption, CO and HC emissions can also be compared on Keillor Road/Saskatchewan Drive for the different objectives. Table 4.10 shows the differences in pollutant costs for the different objectives and the corresponding percentage increase in the pollutants when Keillor Road is open. The table indicates that if the drivers do not have access to Keillor Road than the fuel consumption rate per hour on average is as low as 4 gal/h over all the objectives. The CO and HC emissions are also low where they may be approximated at 85 g/h and 7 g/h, respectively. The increase in vehicles on Keillor Road when the roadway is open results in fuel consumption rates of approximately of 70 gal/h. The CO and HC emissions rates also increase to approximately 1.58 kg/h and 130 g/h, respectively. This increase in fuel consumption is equivalent to 141 vehicles idling for approximately one hour whereas the increase in CO and HC emissions is equivalent to 138 and 114 vehicles idling for 1 hour, respectively.

Furthermore, it is indicated in the table that the pollutants on Keillor Road for the UE_TT assignment and UE assignment based on environmental costs, results in an average increase in vehicular pollutants of 96% when Keillor Road is open. However, if drivers are explicitly told which routes to take from a centralized route guidance system, the increase in pollutant emissions and fuel consumption is approximately 92%. In essence, Saskatchewan Drive is still being used by the drivers from a system perspective in order to ensure that the pollutant emissions on the entire network are minimized even though Keillor Road is closed.

Although the differences in the aggregate travel time and environmental costs do not change significantly, the differences in vehicular pollutants based on different objectives are apparent on 114 Street and Keillor Road as shown in Tables 4.9 and 4.10. Furthermore, Figure 4.7 shows the percentage difference in CO emissions on 114 Street when Keillor Road is open and closed for the different traffic assignment objectives. The reference point on the graph is a SO_CO assignment.

Table 4.10 - Total Environmental Costs on Keillor Road/Saskatchewan Drive When Keillor Road is Open and Closed

			Traffic Assignment Objective			
			TT	Fuel	CO	HC
Fuel Consumed (gal/h)	Keillor Closed	UE	4.19	0.85	1.23	1.34
		SO	7.32	4.14	6.31	5.33
	Keillor Open	UE	68.75	71.02	70.15	70.60
		SO	72.03	71.88	72.26	71.88
	% Increase	UE	93.9%	98.8%	98.2%	98.1%
		SO	89.8%	94.2%	91.3%	92.6%
CO Emissions (g/h)	Keillor Closed	UE	93.45	18.89	27.30	29.75
		SO	163.85	92.29	141.15	119.1
	Keillor Open	UE	1537.5	1588.6	1568.6	1578.4
		SO	1611.1	1607.5	1615.9	1607.8
	% Increase	UE	93.9%	98.8%	98.3%	98.1%
		SO	89.8%	94.3%	91.3%	92.6%
HC Emissions (g/h)	Keillor Closed	UE	7.78	1.57	2.28	2.48
		SO	13.62	7.68	11.74	9.91
	Keillor Open	UE	127.9	132.2	130.5	131.3
		SO	134.0	133.7	134.4	133.7
	% Increase	UE	93.9%	98.8%	98.3%	98.1%
		SO	89.8%	94.3%	91.3%	92.6%

It was found that minimizing the total travel time on the network (SO_TT assignment) results in the lowest CO emissions on 114 Street when Keillor Road is closed. Furthermore, Figure 4.7 also shows that when Keillor Road is closed, the CO emissions on the 114 Street corridor actually increase by 2% if the objective is a UE_CO assignment rather than a UE_TT assignment. It is also indicated by the graph that charging the drivers for the amount of fuel they produce will generate the highest increase in CO emissions where this increase is on the order of 14% given that the reference is a SO_CO assignment. The same graph also indicates that if the drivers are explicitly given their routes based on any of the system objectives (i.e. SO_CO, SO_F, and SO_HC), then the percentage difference in CO emissions is approximately the same. The fact that there exists low percentage differences in CO emissions on 114 Street based on a SO assignment for the different objectives implies that if the system operators route the traffic to minimize fuel consumption or HC emissions (i.e. SO_HC or SO_F), then the SO_CO assignment generates similar link flows and CO emission rates as an SO_HC and SO_F assignment.

Figure 4.7 also shows the trends in the pollutant emissions if Keillor Road is open. In this case, minimizing the total HC emissions on the network generates the lowest CO emissions on 114 Street. Similarly, it is shown that CO emissions on 114 Street are lower if traffic is routed based on a SO_F or SO_TT assignment. This implies that minimizing the total CO emissions on the network does not necessarily mean that all routes will have the lowest CO emissions as indicated by the fact that the SO_F, SO_TT and SO_HC assignment generated lower CO emissions on 114 street.

Furthermore, it is shown that allowing Keillor Road to remain open, but charging the drivers for the amount of CO emissions will actually improve the CO emissions on 114 Street than if the drivers chose their own routes to minimize their travel time as indicated by the fact that CO emissions for a UE_CO assignment increases by 8% and CO emissions increase by 9% for a UE_TT assignment.

Moreover, the percentage difference in CO emissions on Keillor Road/Saskatchewan Drive is shown in Figure 4.8. If Keillor Road is open, the changes in CO emissions on Keillor Road are the same based on a SO assignment. Similarly, if the drivers are charged based on the amount of pollutants they emit (i.e. UE_F, UE_CO and UE_HC assignment), the CO emissions on Keillor Road are approximately 4% lower than if the drivers are explicitly routed to minimizing the total CO emissions. This means that the use of a distributed or centralized route guidance system will not have any adverse effect on driver route choice if the roadway remains available to the public due to the small changes in CO emissions from the SO and UE assignments.

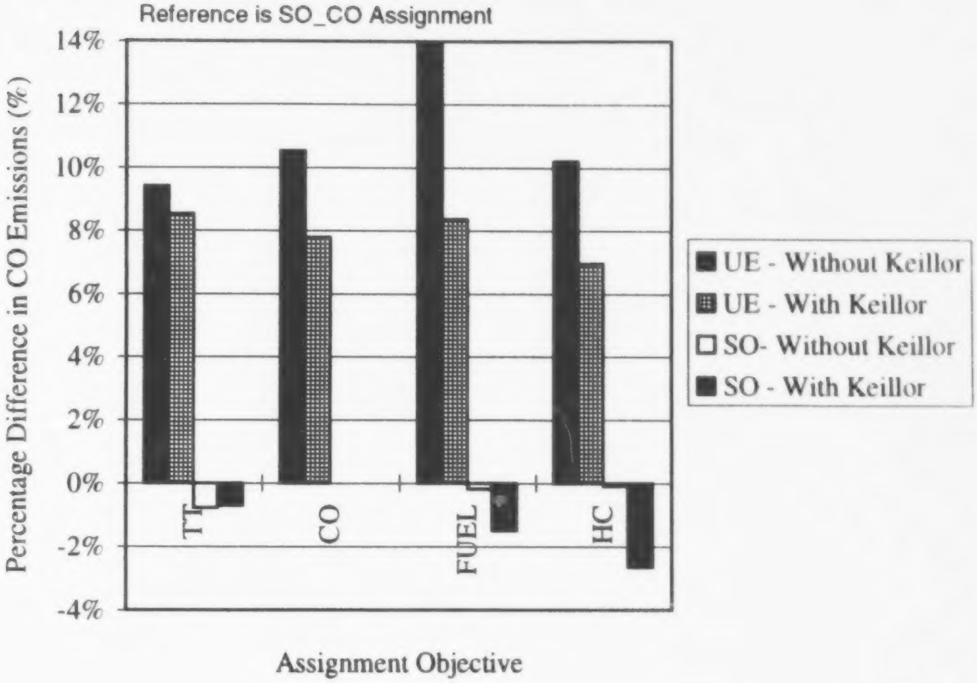


Figure 4.7 - Percentage Difference in CO Emissions on 114 Street Based on Different Traffic Assignment Objectives

However, CO emissions when Keillor Road is closed vary for both the UE and SO assignments based on the different objectives. It is shown on the graph that when Keillor Road is closed, the largest decrease in CO emissions is on the order of 85% based on a UE_F assignment. Similarly, CO emissions are lower by 80% for a UE_CO and UE_HC assignment. This implies that drivers who are actually being charged for the amount of pollutants they emit are not using the Saskatchewan Drive for travelling towards the University or Downtown area when Keillor Road is closed. However, from a system point of view, it is beneficial to use Saskatchewan Drive. This is indicated by the fact that the reduction in CO emission rates when the drivers are routed to minimize the total pollutants on the network is approximately 17% for a SO_HC assignment and 35% lower for a SO_F assignment. It is also indicated on the graph that CO emissions levels actually increase by 17% if the objective is to ensure that the total travel time is minimized on the network when Keillor Road is open.

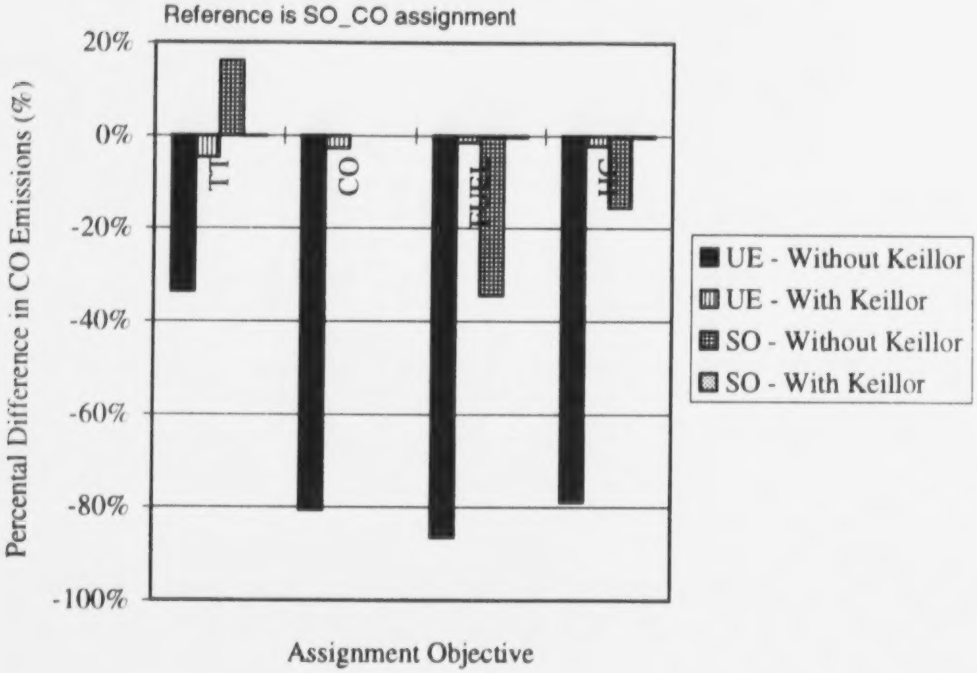


Figure 4.8 - Percentage Difference in CO Emissions on Keillor Road/Saskatchewan Drive Based on Different Traffic Assignment Objectives

It is also important from an engineering perspective to determine how well the model's pollution levels compare with given standards. The EPA (1990) lists standards on the average tailpipe emissions. For CO emissions, the US tailpipe emission standard is 3.4 grams per mile per vehicle and the HC emissions are 0.41 grams per mile per vehicle. These emissions standards are based on a vehicles average speed, acceleration/ deceleration and delay. The ASSIGN model which has adopted generalized cost functions from the TRANSYT -7F model produces CO and HC emissions results for vehicles travelling at average speeds only. Stop and go conditions are not considered and thus the total emissions levels predicted on the network are much lower than the given standards and therefore cannot be compared quantitatively. For example, if the average speed is 30 km/h on the network, the CO emission rates derived from the TRANSYT-7F model is approximately 0.8 grams per mile per vehicle. This value is significantly less than the EPA CO emissions standards of 3.4 grams per mile per vehicle.

4.3.3 Environmental Impact Analysis

In this section, the effect of routing traffic with the traditional objective of minimizing individual user link travel times is examined at an even more disaggregate level than from the previous section. The impact on link flow and CO emissions at intersections within 114 Street and Keillor/Saskatchewan Drive is analyzed when Keillor Road is closed. It is important to examine a UE_TT assignment on a link basis because this analysis clearly shows how the addition of Keillor Road affects the pollutant emissions and link flows at key areas on 114 Street.

The next set of graphs illustrate the increases in link flow and CO emissions on 114 Street when Keillor Road is closed. The increase in link travel time, fuel consumption and HC emissions result in similar trends and therefore, they are not shown. The values on the x-axis represent the intersections that feed the preceding links which were illustrated in Figure 4.6. Table 4.11 list the links that feed into the intersections and their respective codes. This table has been included because it was not possible to include all of the code numbers on the graphs due to space limitations. This table corresponds to each point on the graph where the second column in the table identifies the most southerly intersection where the following links continue in a northerly direction towards 87 Ave. The fifth column identifies the intersection beginning in the northerly direction where the succeeding links represent the movements towards south Edmonton. It should be noted that the code number for each link is divided into two parts. The first part, known as the alphabetical code, identifies the link where T represents a straight through link, R identifies a right turn, L identifies a left turn and M represents a main artery links that connect the intersections. The second part of the code identifies the intersection number that crosses 114 Street.

Table 4.11 - Code Numbers

Direction	Intersection	Link Number	Direction	Intersection	Link Number
Northbound	74 Ave.	M74	Southbound	87 Ave.	M87
		T74			R87
	76 Ave.	L76			T87
		M76			L87
		R76		86 Ave.	T86
		T76			L86
	University Ave.	MU			M86
		RU		84 Ave.	T84
		TU			M84
	82 Ave.	M82			L84
		L82		83 Ave.	T83
		R82			M83
		T82		82 Ave.	M82
	83 Ave.	M83			R82
		T83			T82
	84 Ave.	M84			L82
		R84		University Ave.	TU
		T84			MU
	86 Ave.	M86		76 Ave.	T76
		T86			R76
	87 Ave.	L87			M76
		M87		74 Ave.	M74
		R87			T74
		T87		72 Ave.	T72
					R72
					M72
					L72

Figure 4.9 illustrates the differences in link flow on 114 Street in the northbound and southbound direction. The link flows increase by approximately 600 v/h between 72 Ave. and 82 Ave. when Keillor Road is closed and increase by 150 v/h between 82 Ave. and 87 Ave. The decreasing trend in link flow between 82 Ave. and 87 Ave. is due to the fact that drivers have other route options. In the southbound direction, link flows increase only between University Ave. and 72 Ave where the maximum increase in link flow is on the order of 100 v/h.

It may be seen in Figure 4.10 that there exists an increasing trend in CO emissions of approximately 60 g/h on 114 Street in the northbound direction between 72 Ave. and

82 Ave due to the increase in link flow shown in Figure 4.9. However, increases in CO emissions on 114 street in the southbound direction are small where the highest CO emission increase is on the order of 20 g/h between 76 Ave. and 72 Ave.

In terms of travel time, it was found from the model results that the increase in travel time on 114 Street is on the order of 15 seconds in the a.m. peak hour for the through vehicles. This increase is determined by summing the link travel times in the northbound direction for all through vehicles from 72 Ave. and 87 Ave. The low increase in travel time is due to the fact that the model is a macroscopic steady state equilibrium model where travel time is determined based on average speed data information for the hour modelled and therefore it is expected that the delay on 114 Street generated from the model results would be lower than the actual calculated delay from the individual vehicles.

Moreover, Figure 4.11 illustrates the difference in link flow on Keillor Road and Saskatchewan Drive. It should be noted that the x-axis is coded in the same format as the graphs that represented the results of 114 Street where, for example, RFOX represents a right turn link that feeds into Fox Drive.

In the northbound direction, the model shows that when Keillor Road is open approximately 800 v/h would use this roadway to get the University area or Downtown from south Edmonton. This link flow pattern is directly related to the decrease in flow on 114 Street if Keillor Road is open. Link flows in the southbound direction for the a.m. peak hour, however, do not have any bearing on the overall results. It is found that the average increase in link flow is on the order of 100 v/h in the southbound direction.

Furthermore, Figure 4.12 illustrates the reduction in CO emissions on Keillor Road/Saskatchewan drive when Keillor Road is closed. It is indicated on the graph that if Keillor Road is closed, vehicular pollutants decrease on the order of 400 g/h between 76 Ave. and University Ave. in the northbound direction. It is also found that the decreases in CO emissions in the southbound direction is on the order of 100 g/h. Therefore, it is shown in this section that by analyzing the effects on link flows and CO emissions on 114 Street and Keillor Road at a disaggregate level, the closure of the roadway directly influences link flow and CO emissions at key areas along 114 Street.

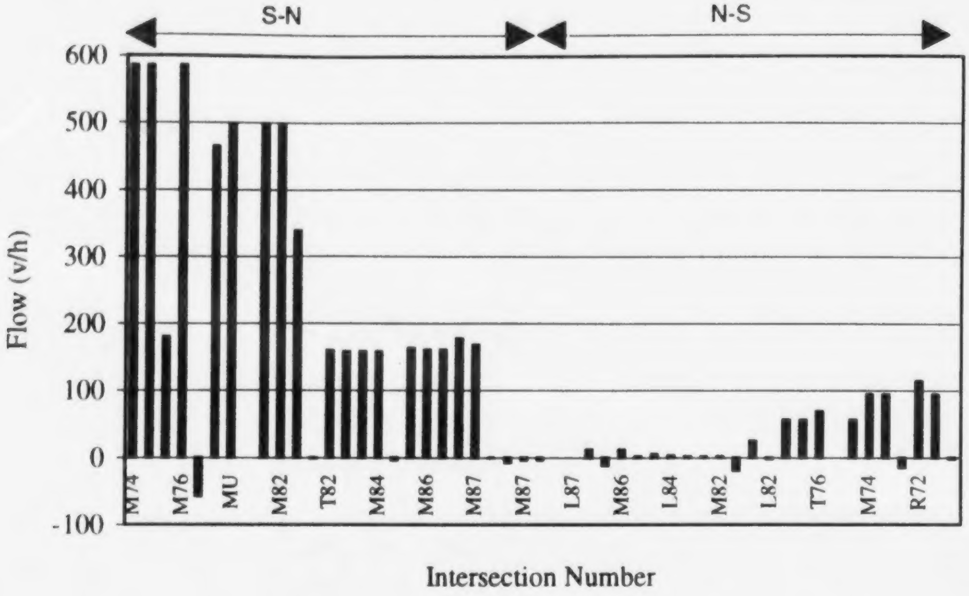


Figure 4.9 - Link Flow Difference on 114 Street when Keillor Road is Closed

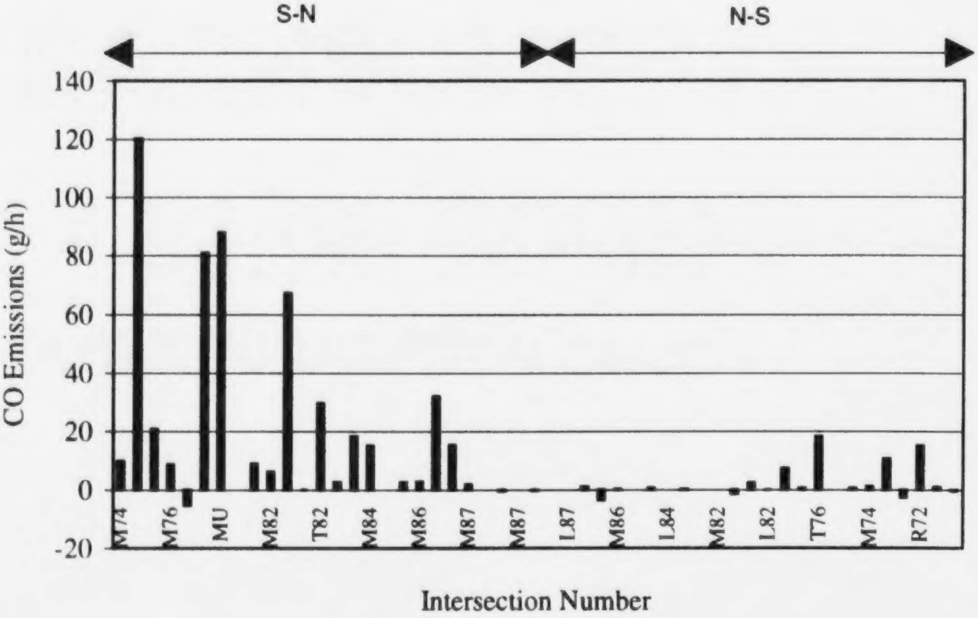


Figure 4.10 - Total CO Emissions Difference on 114 Street when Keillor Road is Closed

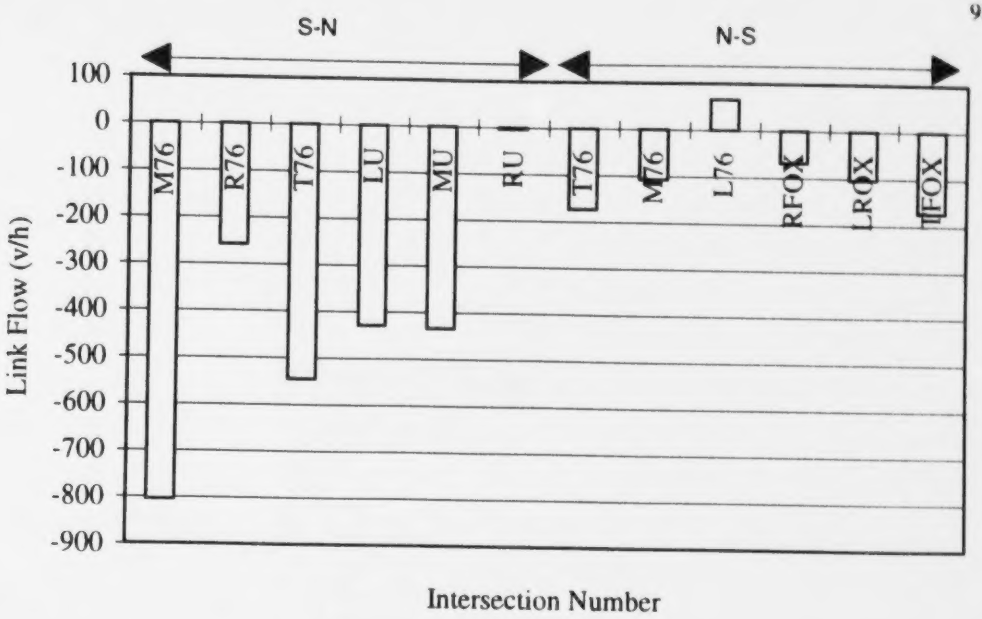


Figure 4.11 - Link Flow Difference on Keillor Road and Saskatchewan Drive when Keillor Road is Closed

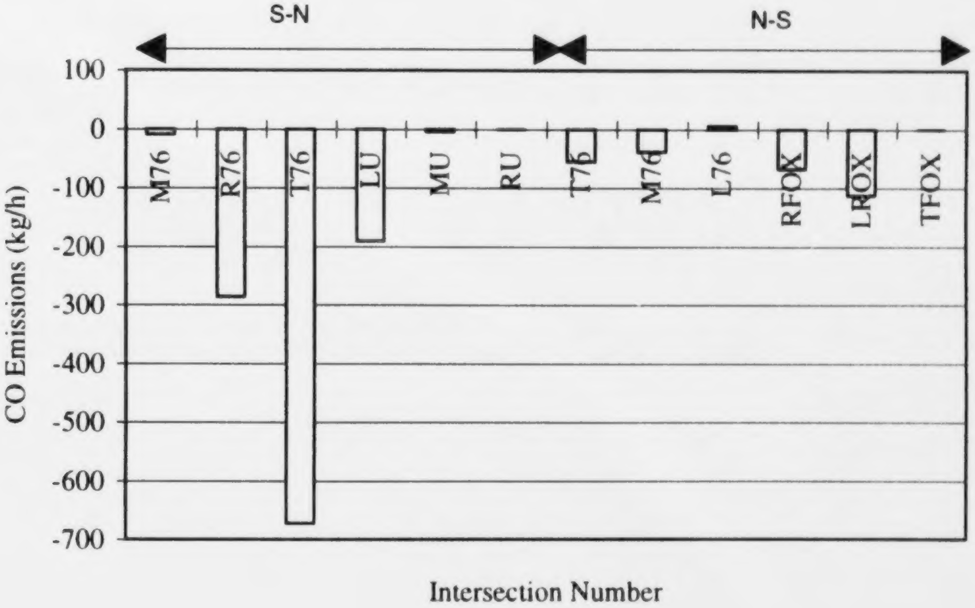


Figure 4.12 - Total CO Emissions Difference on Keillor Road and Saskatchewan Drive when Keillor Road is Closed

4.3.4 Demand Rate Analysis

In section 4.3.1 and 4.3.2, it was found that the changes in total system costs at the present demand level is small (i.e. less than 1%) but significant changes in costs were illustrated for the individual routes such as on 114 Street and Keillor Road when different assignment objectives are implemented into the model. In this example, it is assumed that transportation engineers want to examine the long term pollution emission trends if the demand levels increase or decrease. In the following example, the demand levels for the University network vary from 50% of the present demand level to double the present demand level. This results in a lightly loaded network to a heavily congested network. Table 4.12 shows the weighted average v/c ratio for each demand level.

Table 4.12 - Key to Demand Rates for the University Network

Demand Level	Weighted Average V/C
1	0.19
2	0.23
3	0.38
4	0.41
5	0.45
6	0.47
7	0.56
8	0.69
9	0.78
10	0.85

Figure 4.13 illustrates the percentage increase in total system travel time if drivers are routed on the network to minimize their own generalized cost or if drivers are routed by system operators to obtain minimum congestion levels and pollutant emissions. The total travel time on the network is compared such that the reference condition is a SO_TT assignment. This is shown as a straight line function equal to zero. Figure 4.13 indicates that the increase in total system travel time is the highest when the objective is to minimize individual fuel consumption. The increase in travel time, however, is less than 1.2%. It is also indicated on the graph that for high demand levels, the travel time on the network for

a SO_CO, SO_TT and SO_F assignment is the same. Furthermore, if the drivers are explicitly routed based on environmental objectives or they are charged based on the amount of pollutants they produce, it is shown that the travel time on the network is actually higher than the travel time produced from a UE_TT assignment. This increase, however, is on the order of less than 1%. Therefore, for this network, it seems that the effect of routing traffic based on different objectives for any demand level does not adversely increase the link travel times.

Figure 4.14 illustrates the effect of CO emissions levels on the network based on different objectives. It is shown on this graph that routing traffic to minimize pollutants such as fuel consumption or CO emissions does not adversely vary the CO emissions levels on the network. The highest increase in CO emissions levels is on the order of 0.35% when the objective is a UE_F assignment. It is also indicated on the graph that minimizing the total fuel consumption on the network is similar to the objective of minimizing the total CO emissions as indicated by the average increase in CO emissions levels of less than 0.05%.

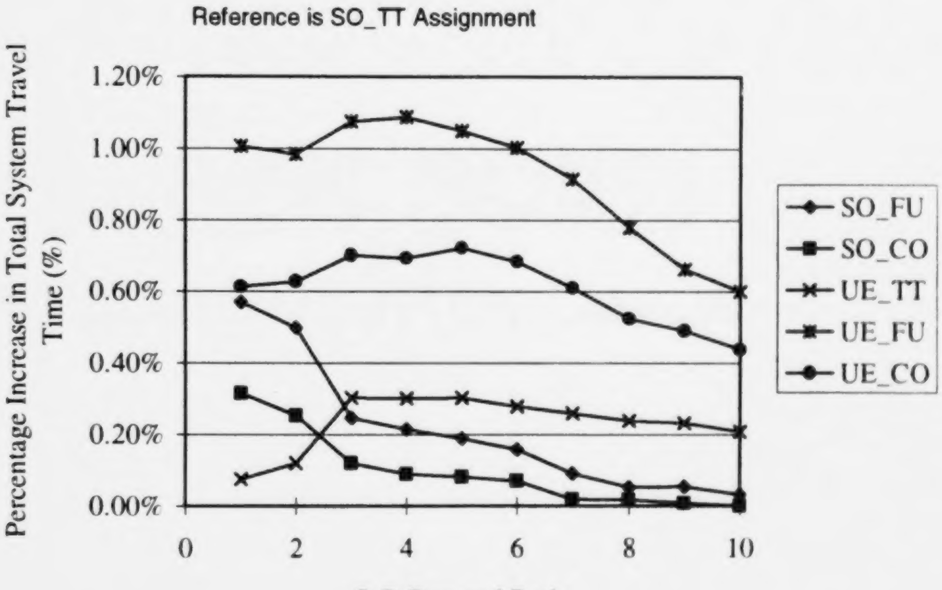


Figure 4.13 - Percentage Increase in Total System Travel Time vs. Demand Level on the University Network

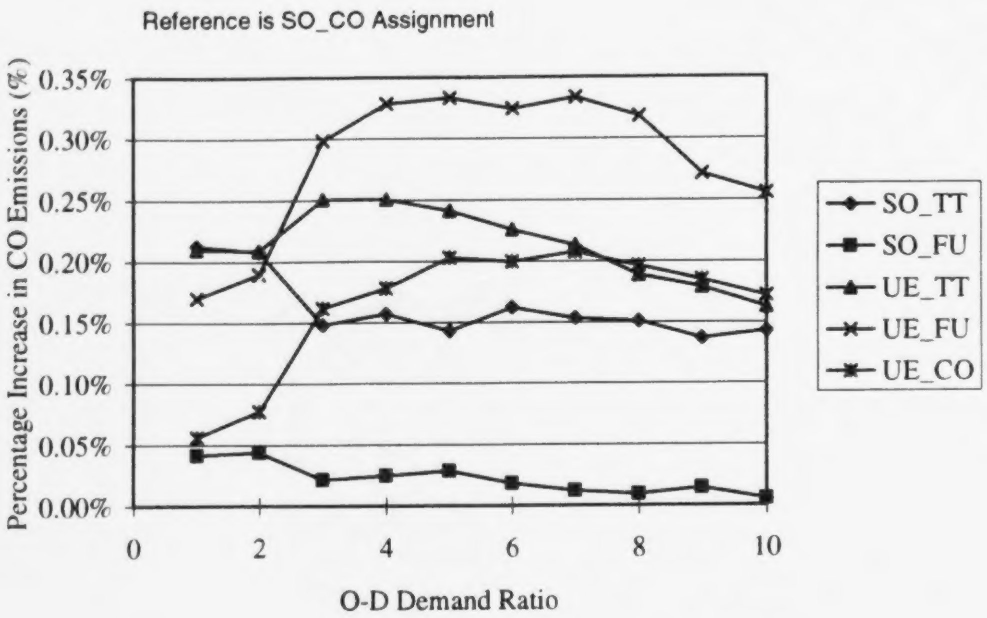


Figure 4.14 - Percentage Increase in CO emissions vs. Demand Level on the University Network

A second network which represents the City of Ottawa, Canada, was chosen in order to examine whether the same trends would occur as on the University network if the environmental objectives were used to route the traffic. The Ottawa network represents a much larger area than the University network. The network consists of 1402 links, and 636 nodes where the total km - length is 749.7 km. The links that represent Ottawa consist of high speed arterial roadways and freeways. The Ottawa Network is shown in Figure 4.15. It is assumed that the demand rates vary based on an weighted average volume to capacity ratio as shown in Table 4.13.

Table 4.13 - Key to Demand Rates for the Ottawa Network

Demand Level	Weighted Average V/C Ratio
1	0.19
2	0.33
3	0.49
4	0.62
5	0.78
6	0.91

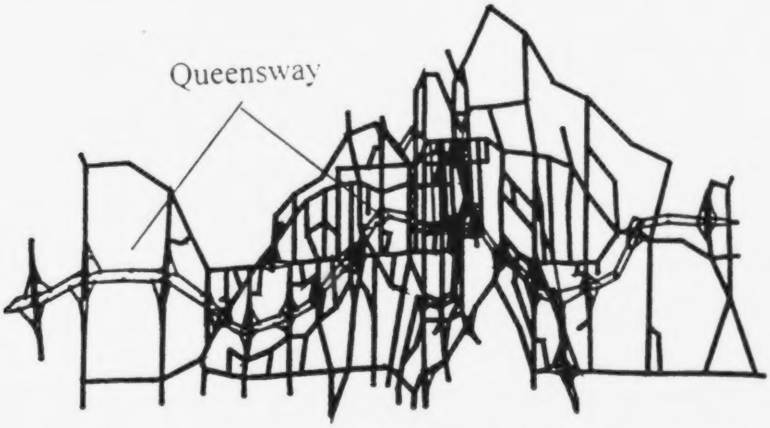


Figure 4.15 - Ottawa Network

Figure 4.16 illustrates percentage increase in total system travel time for the different objectives which include travel time, fuel consumption and CO emissions. The relationship between the SO_TT and UE_TT is concave with the biggest difference on the order of 1%. If the objective is to minimize the total amount of CO produced (SO_CO), the total system travel time increases between 1.5 to 4%. In general, however, as the demand rate increases the system travel time decreases for the objective SO_CO. Similarly, an assignment based on SO_F results in overall travel time increases between 10 and 5% where the trend decreases as the demand increases.

The largest difference in overall system travel time occurs when the objective is to charge the drivers based on the amount of fuel consumed (i.e. UE_F assignment) where an increase of 24% in travel time occurs in the congested regions. If the drivers are allowed to choose their routes individually and their decisions are based on minimizing the amount of CO produced (UE_CO), then the total system travel time would increase starting at 4% in the low congested regions to 12% when the demand level is high.

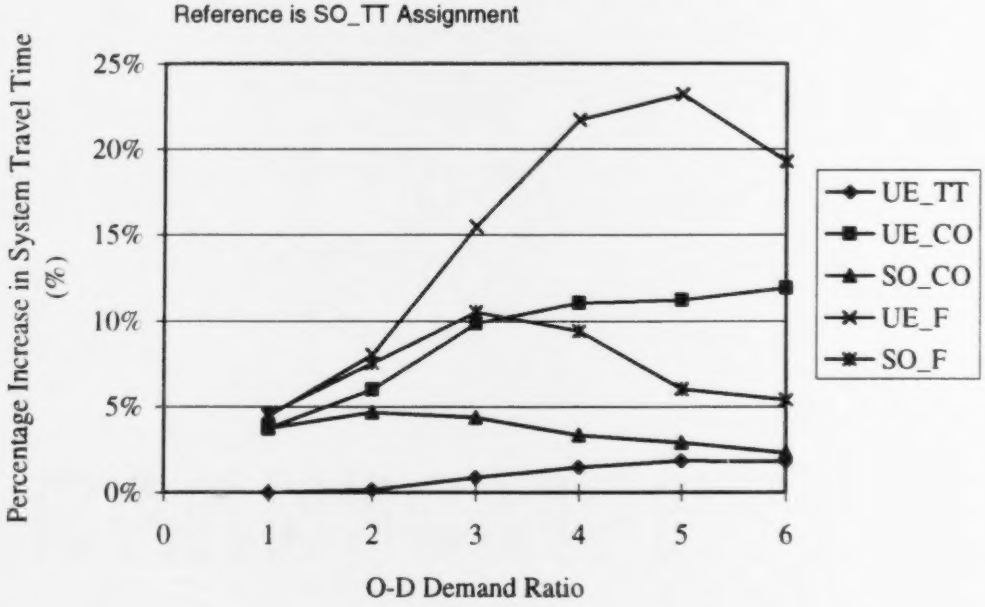


Figure 4.16 - Percentage Increase in Total System Travel Time vs. Demand Level on the Ottawa Network

Figure 4.17 shows the percentage increase in CO emissions as the demand level increases. At high demand levels, the UE_TT assignment results in very similar CO emissions when the assignment is a SO_CO. However at lower demand levels, traffic that is being routing to minimize their own travel time, the CO emissions increase to approximately 2.5 %. This implies that in congested networks the UE_TT objective results in CO emissions levels that are approximately equal to what would be achieved if the vehicles were directly routed to minimize CO levels with a centralized route guidance system.

However, if traffic is routed by a distributed route guidance system such that the individual users minimize their own CO emissions, the CO emissions levels are similar to an assignment where a centralized route guidance system is used to minimize the total CO emissions (SO_CO) for low demand levels. As the demand levels increase, the CO emissions increase in a linear manner where the difference in CO emissions between a SO_CO and UE_CO reaches 1.5% at the highest demand level. It is also found that the UE_CO emissions for higher demand levels are actually higher than if the vehicles are routed based solely on minimizing their own travel time. This result is counter-intuitive in that it implies that at high congestion levels routing traffic to minimize user CO production levels might actually increase the overall CO emissions. A similar result was found in the simple two link example as shown in section 4.2.

If CO emissions levels are not considered in the centralized route guidance system and the main objective is to route travel to minimize travel time (SO_TT assignment), then CO emissions increase by 3.5%. The relationship is convex where the minimum difference in CO emission increase is 1.5% which occurs in the middle demand level and the highest increase in CO emission is 3.5% at the highest demand level. This implies that if a route guidance system was instituted with the sole purpose of minimizing travel time, other system objectives that are assumed to also improve might actually be worse off.

It is also indicated on the graph that the SO_CO emissions levels on the network are similar when the objective is to ensure that the total fuel consumption rate is minimized (i.e. the relationship is concave with the highest difference on the order of 0.5%). Furthermore, if the objective is to route the drivers to ensure that they minimize their own rate of fuel consumption, then the CO emission levels are similar to an SO_CO objective at low demand levels and reach an increase of 4% at the high demand levels.

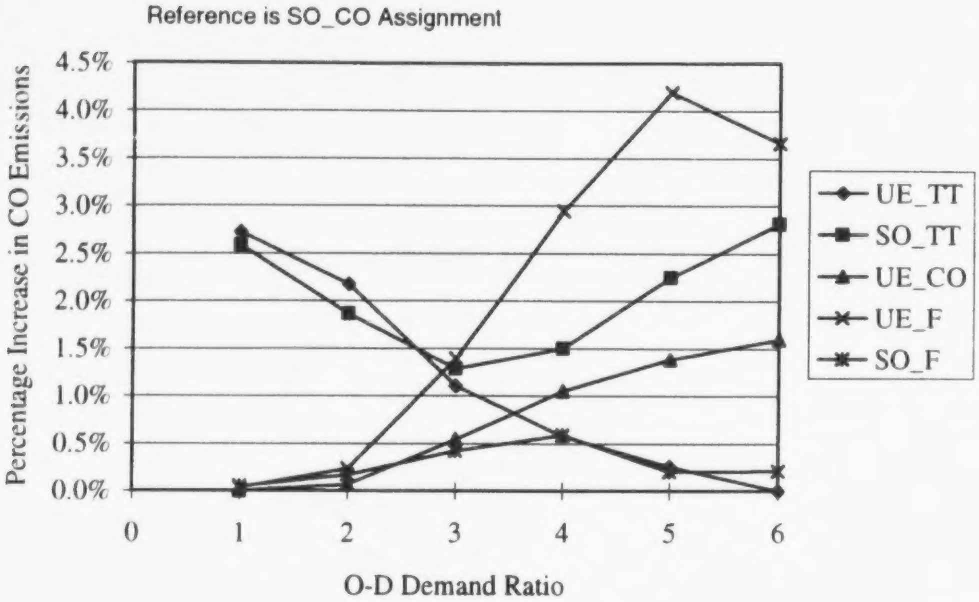


Figure 4.17 - Percentage Increase in CO emissions Levels vs. Demand Level on the Ottawa Network

4.4 Conclusions

1. The primary aim of this chapter was to illustrate the importance that different objectives can have on the operation of a traffic system. It was shown in the simple two link example that objectives that would seem to be complementary, for example, the reduction in travel time and the reduction of pollutant emissions, may actually conflict.

2. Each network acts independently and trends experienced for one network may not necessarily be the same for another network. This was found when the environmental costs on the network were compared for the Ottawa and the University network based on a demand rate analysis. The output statistics from the University network resulted in similar trends in pollution levels and total system travel time for any assignment objective and demand level. The largest difference in CO emission levels was on the order of 0.35%

which occurred when the objective was a UE_F assignment. The largest difference in system travel time was 1.2% which also occurred for a UE_F assignment. This implied that using ITS technologies to route traffic based on environmental objectives would be the same as using this technology to reduce congestion (travel time) on the network. Moreover, the low percentage differences in total travel time and CO emissions is due to the minimum routing options on the network.

3. The CO emissions and total travel time on the Ottawa network resulted in different trends than in the University network. A much wider range in travel time and CO emissions for the same analysis was found because of the higher operating speeds and larger network. In this example, if the objective was to reduce CO emissions because the drivers may be charged on the amount of CO they produced, the overall travel time increase was linear where the travel time difference reached a peak at 12% at high demand levels for a UE_CO assignment. Similarly, at congested levels on the network, the overall increase in CO emissions were higher than if the drivers routed themselves based on minimizing their own travel time. This implied that charging drivers for emissions may actually make the system worse off from an environmental perspective.

4. At a more disaggregate level, the pollutant emissions and route travel times were compared for 114 Street and Keillor Road to determine the effect the closure of Keillor Road may have on the route costs. It was found that when Keillor Road is closed, the CO emissions on 114 Street increased by approximately 20% for a UE assignment and 18% for a SO assignment where the assignment is based on different objectives. On a relative scale, the CO emissions on Keillor Road decreased by 96% for a UE assignment and 92% for a SO assignment.

5. The impact of adding of removing Keillor Road on the University network causes some significant changes in individual link flows, travel time, and environmental conditions at certain locations along the 114 Street Corridor and Keillor Road. The analysis was done on a link basis to determine where the critical regions may occur if Keillor Road is closed.

It was found that link flows increased on average by 600 v/h between 72 Ave. and 82 Ave. and increased by 150 v/h between 82 Ave. and 87 Ave. in the northbound direction when Keillor Road was closed. The increase in link flow on 114 Street due to the closure of Keillor Road was directly related to the increase in fuel consumption and pollutant emissions. The increase in CO emissions, for example was approximately 60 g/h. Furthermore, it was also found that there is on average a 2% increase in pollutant emissions and a 2.9% increase in overall travel time on the network when Keillor Road is closed.

Chapter 5 - Equitable Traffic Assignment

5.0 Introduction

This chapter examines the impacts on the route flows and pollution levels for traffic routing strategies based on an equitable traffic assignment model. In this thesis, equity is defined as the routing of traffic in order to meet the objectives of the people living adjacent to the roadways. For example, ensuring that the vehicle emissions in residential areas are the same is one form of a system equitable assignment where operators could use route guidance technologies to accomplish such routing strategies.

In this chapter, an equitable assignment within the University network is examined on the basis of obtaining the same aggregate effects as closing the roadway (another equitable measure). In the example problem Keillor road remains open, but drivers are routed on the network such that the pollutant emissions are the same on 114 Street and Keillor Road.

This chapter is divided into four sections. First, the theoretical concepts of equity are described. Second, the aggregate travel time and link flow results for the University network are compared for the incremental and convex combinations algorithm because it is proposed in the thesis to use the incremental traffic assignment algorithm to model traffic routing strategies from an equitable perspective. Third, two sample problems are used to illustrate the concept of equity. The first example compares the incremental traffic assignment model with an analytical solution when non-conventional objectives (i.e. noise pollution) and constraints (i.e. multiple user classes) are used within the model. The second example presents the solution of a system equitable assignment for the simple network illustrated in Chapter 4. Finally, the effects on the total pollutant costs on the University network and the pollutant costs on 114 Street and Keillor Road are analyzed for an equitable traffic assignment perspective.

5.1 Equity Concepts in Traffic Assignment

There are a wide range of equity definitions (Rilett, Hutchinson, and Haas, 1988) in transportation engineering. For this thesis, an equitable traffic assignment may be defined as the routing of traffic through a network using the objective of the residents of a neighbourhood rather than the system operators or drivers (Rilett, 1993). It should also be noted that equitable traffic assignment modelling used to route automobiles within urban networks has not been examined previously. With the changes in peoples' attitude towards the environment and the advances in ITS technologies, it is therefore possible to achieve such equitable routing strategies.

It is useful at this point to examine how an equitable assignment may be achieved. As an example, consider the people living near major roadways. They may wish that the system operators route the traffic through a network such that the total noise levels or vehicle emissions on the adjacent streets do not exceed some maximum safety standard (Rilett, 1993). In this instance, constraints to the generalized cost function would involve adding an upper limit on the noise levels or vehicle emissions rather than adding a limit to the number of vehicles allowed on the street.

In another example, the people in the city may wish that all the vehicles on the network be assigned such that the noise levels or vehicles emission levels in several residential areas are the same. This objective would involve the concerns of the general public and UE or SO objectives would no longer be applicable.

It is proposed in this thesis to use a modified incremental traffic assignment technique to solve traffic routing strategies from equitable perspectives. The incremental assignment model may overcome some of the constraints of the Frank-Wolfe algorithm. For example, it was briefly mentioned in Chapter 4 that the convex combinations algorithm may in fact not obtain an optimal solution if environmental generalized cost functions are used in the traffic assignment model because of the non convex nature of the generalized cost function that describes the environment. In addition to this problem, the theory behind the UE mathematical formulation as discussed in Chapter 2 does not allow multiple user classes to be modelled and additional constraints to the UE program are therefore necessary. For example, the effects that trucks may have on a route may alter the route choices of other drivers that use lighter vehicles and thus link flows generated in an assignment process may be significantly different. An example problem where the effect of noise pollution created by trucks and the effect of routing traffic to ensure that the noise levels are equal on a network will be illustrated in section 5.3. It will be shown that the incremental assignment model is suitable if the assignment model has additional constraints and non-conventional objectives.

The incremental assignment can be readily implemented for more complex traffic assignment problems that do not follow the constraints stipulated from the convex combinations assignment technique. A traffic assignment model that has used the concept of the incremental assignment is the well-known CONTRAM continuous traffic assignment model developed in England. The incremental assignment technique was developed in the 1960's but was discarded because the Frank-Wolfe algorithm developed in the 1970's guaranteed an optimal solution. However, the incremental assignment may be adequate given new constraints.

The next section of this chapter will demonstrate that the incremental assignment technique results in a solution similar to one generated by the convex combination algorithm for the University network. This example validates the incremental assignment algorithm for later use when ASSIGN is used to model the University network based on the equitable principles defined above.

5.2 Convergence of the Incremental Traffic Assignment Algorithm on the University Network

The incremental traffic assignment algorithm was coded into the ASSIGN model for purposes of routing traffic from equitable perspectives. The algorithm is similar to the one presented in Chapter 2 and may be shown by the following flow chart in Figure 5.1.

The objective of this section is to validate the incremental assignment algorithm used within the ASSIGN model. The University network is used as a test bed. The test is conducted as follows:

1. The number of increments or iterations are increased by powers of 2
2. For each test, the solution to the user equilibrium assignment based on minimizing travel time is recorded and plotted.
3. The link flow results for the convex combinations algorithm and incremental assignment are compared based on a regression analysis where 30 increments and iterations are used within the models.

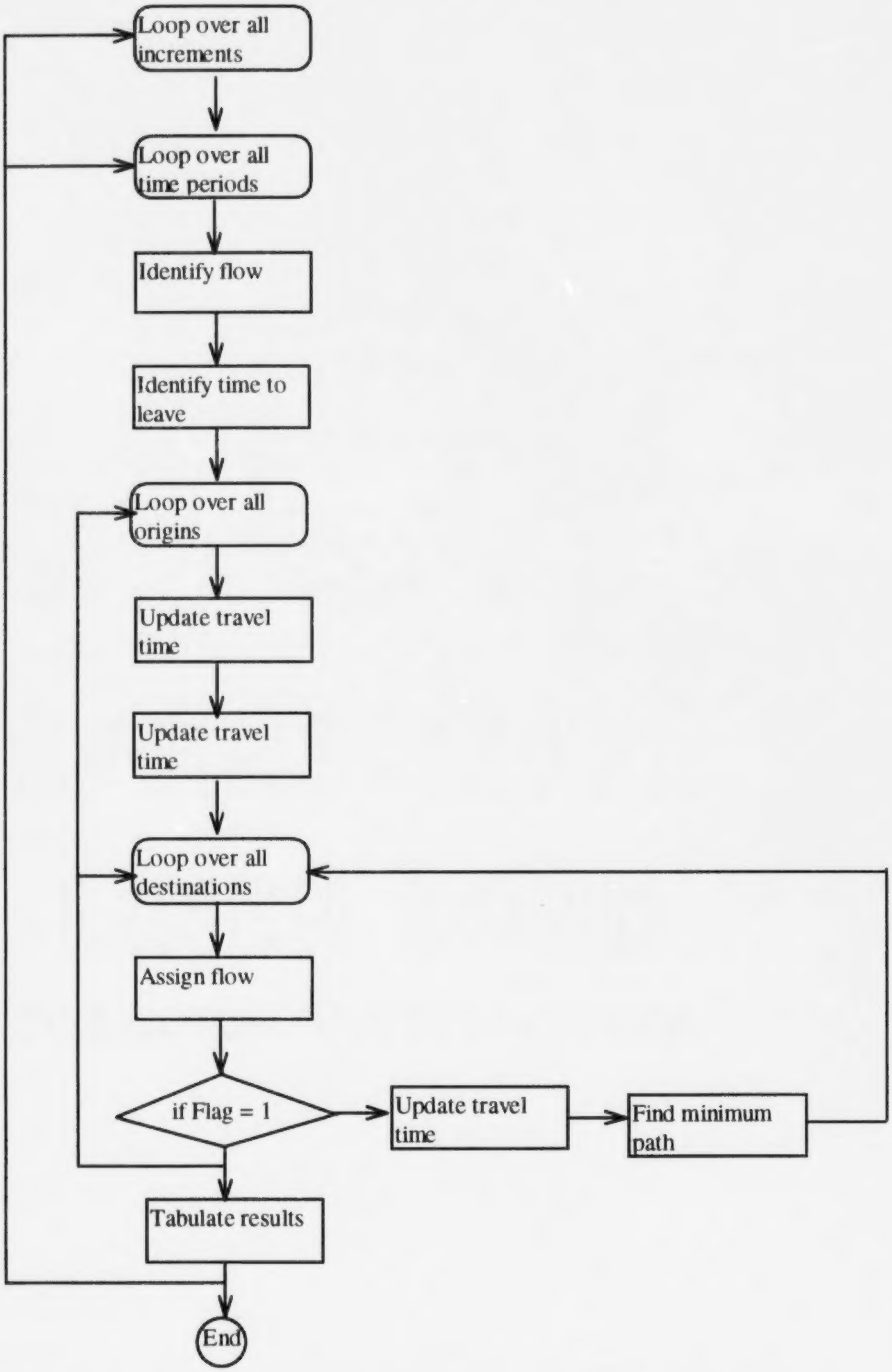

Loop over all increments
Loop over all time periods
Identify flow
Identify time to leave
Loop over all origins
Update travel time
Update travel time
Loop over all destinations
Assign flow
if Flag = 1
Update travel time
Find minimum path
Tabulate results
End

Figure 5.1 - Incremental Traffic Assignment Flow Chart in ASSIGN

Figure 5.2 shows the results of the user equilibrium travel time on the University network as the increments increase for both the convex combinations and incremental assignment. The user equilibrium assignment solution is the area under the travel time function (i.e. the solution is the sum of the integral of the travel time as a function of flow on each link). It is shown in Figure 5.2 that the UE link travel times converge as the iterations or increments increase for both the incremental and convex combinations algorithm due to the slight changes in slope on the graph. For example, the change in the user travel time is on the order of 0.04% between the results of the incremental assignment for 8 and 16 increments. A similar trend is found with the solution of the convex combinations algorithm where the change in the user travel time is on the order of 0.02% between an assignment of 8 and 16 iterations.

It should also be noted that at one iteration, the convex combinations algorithm is an all-or-nothing assignment where the travel time is 2247 veh-hours. However, an incremental assignment with one increment generates a lower overall UE travel time of 2160 veh-hours. The discrepancy between the two algorithms comes from the fact that the incremental assignment updates the link travel times for each O-D pair. That is, the incremental assignment is pseudo-dynamic where the background traffic will influence the route selection for different O-D pairs given the same increment number.

Furthermore, it is found that for 8 iterations in the convex combinations algorithm, the user equilibrium travel time is lower than for the incremental assignment with the same number of increments. However, the difference in the user equilibrium travel between the convex combinations and incremental assignment algorithm is on the order of 0.23% in the final increment. This implies that the difference in link flows between the incremental and convex combinations algorithm is similar as shown in the next paragraph.

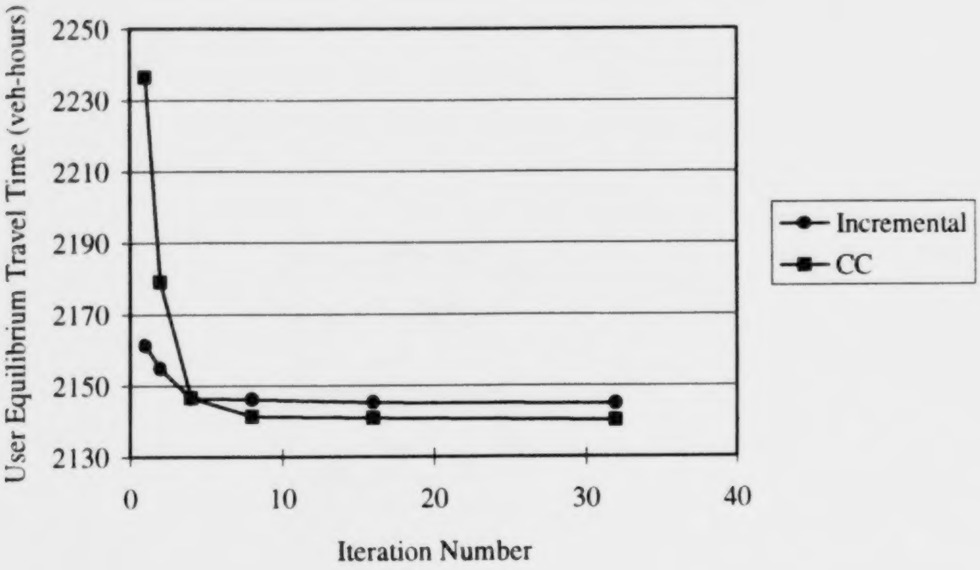


Figure 5.2 - Convergence of the User Equilibrium Travel Time Results for the Incremental and Convex Combinations Algorithm

Figure 5.3 is a scatter plot of the link flow results from the incremental and convex combinations algorithm. It is shown in Figure 5.3 that there is a strong correlation between the link flows for the two assignment algorithms due to the fact that the scatter points fall right on the 45° line. Furthermore, the results in an R^2 between the predicted least squares line and the actual data was found to be 0.999.

From the above analysis where the total travel time and link flow results were examined and from the arguments presented in the previous section, the incremental assignment is, in fact, a more suitable to model equity and multiple user class type problems. It is shown that the incremental assignment solution for a traditional UE assignment is similar to the solution presented from a convex combinations algorithm given the same network and travel time objective.

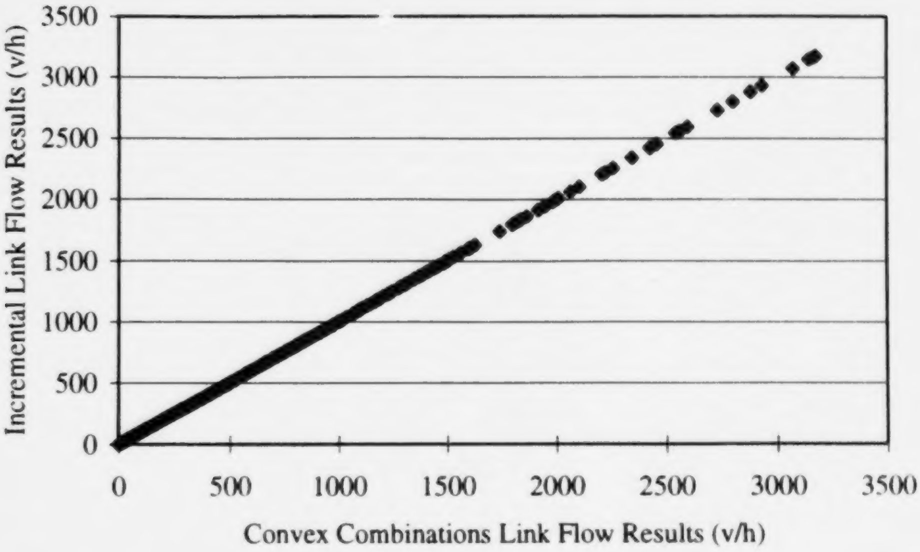


Figure 5.3 - Scatter Plot of the Incremental and the Convex Combinations Link Flow Results

5.3. Modelling an Equitable Traffic Assignment for Simple Networks

The concept of an equitable traffic assignment is illustrated on two different sample networks. First, the concept of equity is presented for a simple two link network where the objective is to ensure that noise levels are equal for all the residents that live adjacent to an arterial and freeway route. This example illustrates the equity concept and shows that the incremental traffic assignment model generates results similar to an analytical solution when non-conventional objectives and multiple user classes are defined in the example problem. Second, the two link network presented in Chapter 4 is extended to include the results from a system equitable assignment for CO and HC emissions.

5.3.1 Equitable Traffic Assignment for a Simple Two Link Example Problem - One Highway, One Arterial

In the example problem, a two link network is used to introduce how the incremental assignment algorithm may be used to model multiple user classes and the concept of an equitable assignment. The sample network is similar to the network shown in Figure 4.1 of Chapter 4. In this section, link 1 is a highway route which bypasses a city while link 2 is a slower arterial roadway that passes directly through the city. In the example, link 1 is a freeway which consists of 2 lanes with a capacity of 2000 v/h/lane and a length of 10 km. The arterial roadway, link 2, has a capacity of 2000 v/h/lane and a link length of 4 km. The free flow travel time for the freeway and the arterial is 8 minutes and 6 minutes, respectively. The origin destination demand from node 1 to node 2 is 6000 v/h. Of the 6000 vehicles originating from node 1, 8% of the vehicles are classified as medium trucks and 2% are classified as heavy trucks.

The objective of the analysis is to identify the link flows when the noise pollution function shown in Equations 2.26a and 2.26b are used as the generalized cost functions in the traffic assignment model. It is assumed that the buildings along the freeway are placed at a distance of 60 m from the measurement point and 50 m from the junction (J). The buildings along the arterial roadway are 20 m from the measurement point and 5 m from the junction.

The objective of the traffic assignment is to route the vehicles such that the noise pollution levels are the same for the people living near link 1 and link 2. To illustrate this concept, assume that the traffic department decided to route all trucks (200 trucks/h) to link 1 (freeway) by means of a truck route. The remaining vehicular volume (i.e. the automobiles) is then assigned onto the network such that the noise levels are the same on both links. The main factor that is considered in this example is to see whether the link flows and noise levels change on the roadways when the percentage of the total truck volume diverted onto the freeway increases given the same assignment objective.

Based on the above information, Table 5.1 shows the analytical and incremental assignment results for the sample problem where the noise levels on the two routes are equal given different truck percentages assigned onto the freeway. The table indicates that the noise levels on the two links do not reach equivalency until 50% of the total truck volume is assigned onto the freeway link. If the percentage of total truck volume is less than 50% on the freeway, the noise levels on the arterial roadway are much higher than the freeway noise levels and a system equitable assignment cannot be achieved. For example, when all of the trucks use the arterial roadway, the noise level on the arterial is 76.1 dB(A) and only 72.3 dB(A) on the freeway.

Table 5.1: Analytical and Incremental Assignment Based on Noise Level for Different Percentages of Total Trucks on the Freeway

	Analytical Solution			Incremental Solution		
% of Total Trucks on Link 1	Flow on Link 1 (v/h)	Flow on Link 2 (v/h)	Equilibrium Noise Level (Leq)	Flow on Link 1 (v/h)	Flow on Link 2 (v/h)	Equilibrium Noise Level (Leq)
0	No Equivalent Noise Level					
10						
30						
50	5660	340	72.71	5646	354	72.71
70	5230	770	72.02	5226	774	72.02
90	4785	1215	71.31	4779	1221	71.32
100	4560	1440	70.95	4542	1458	70.95

When the total truck volume on link 1 is greater than 50%, a percentage of the lighter vehicular traffic flow is assigned onto the arterial roadway. At 50% of the total truck volume on the freeway, the noise levels on both the arterial and freeway reach an equivalent value of 72.71 dB(A), and when all of the trucks are assigned onto the freeway, the noise level is the lowest at 70.95 dB(A). As would be expected, given the relevant coefficients for truck traffic in Equations 2.26a and 2.26b, the arterial roadway is more susceptible to changes in noise level for a given change in flow than the freeway. It is also indicated from the table that the decrease in total volume on the freeway drops by 16% when all of the trucks are assigned onto the freeway.

However, if travel time on the links is considered, then some concerns may arise by the users of the freeway. If, for example, the decision was to assign 100% of the total truck volume to the freeway, and the objective is to ensure that the noise levels on both routes are equal, then the travel time for the drivers on the freeway would be 10.03 minutes while the drivers of the arterial roadway would experience a travel time of 6.24 minutes. In this example, the drivers on the freeway (link 1) experience a 16% increase in travel time if the objective is to ensure that the noise levels are equal on both routes. If a traditional UE_TT assignment is performed, the flow on link 1 would be 3390 v/h and 2610 v/h on link 2 where the travel time would be 8.61 minutes on both routes. The noise levels, however, based on a UE_TT assignment would be 69 dB(A) on the freeway and 79.1 dB(A) on the arterial roadway. This implies that the traditional UE_TT assignment and SE assignment are not complementary.

As shown in Table 5.1, the incremental assignment technique yields results very similar to those from the macroscopic analytical solution. The percentage difference in link flows and noise levels between the macroscopic and the incremental solution is on the order of less than 1 %.

5.3.2 Equitable Traffic Assignment Model Based on CO and HC Emissions for the Two Link Network Presented in Chapter 4

In addition to the noise example in the previous section, the simple two link network shown in Figure 4.1 may also be used to compare the overall pollution levels, route volumes and route travel times based on a SE, UE and SO assignment. This example problem illustrates the differences in CO and HC emissions given that the route guidance technologies are applied to generate equal pollution levels on each route.

Table 5.2 illustrates the difference in link flows and CO emissions when the objective is to minimize CO emissions based on a UE, SO, and SE assignment. If the objective of the assignment is to ensure that both routes have equal CO levels (SE) then 3982 v/h would be assigned on route 1 and 4018 v/h on route 2 as indicated in Table 5.2. The change in route flows increases the total CO emitted by 14% to 7.1 kg/h where the reference a SO_CO assignment. The difference in route flows between the SE_CO and SO_CO solution is approximately 25%. However, the SE_CO and UE_CO solutions generate similar results in terms of route volumes where the difference is on the order of 0.4%. Furthermore, it is found that if the drivers are routed to ensure that the CO emissions are equal on both routes, the link travel time on route 2 would increase by approximately 109% from the example where the drivers minimized their own link travel times. Therefore, to achieve a SE assignment objective, the drivers would have to be explicitly assigned on the network because drivers would be unwilling to increase their travel time in order to obtain equitable measures on the network.

Table 5.3 illustrates the relationships of the UE, SO and SE assignment solution for HC emissions. Similar to the trends for CO emissions, an SE assignment used to ensure that the HC emissions are equal results in similar link flows as a UE_HC assignment. The difference in on the order of 1.1%. It is also found that the difference in link flows between the SE_HC and SO_HC assignment is approximately 23%. From the SE assignment, the link travel time on route 2 is 111% higher than if the drivers routed themselves to minimize their own travel time. It is also indicated in the table that the travel time on route 2 is 129 seconds higher than on route 1 and therefore unless the drivers are explicitly told which route to take based on obtaining a SE objective, it would be unlikely that drivers would follow this routing combination due to the large difference in travel time on the links.

Table 5.2 - Assignment Based on CO Emissions

Type	Route	Volume (v/h)	Rate (g/v)	Travel Time (s)	Total (kg)
SO	1	5161	0.8839	102	6.09
	2	2840	0.5378	96.5	
UE	1	3966	0.8922	82	7.14
	2	4034	0.8922	209	
SE	1	3982	.8919	83	7.10
	2	4018	.8841	207	

Table 5.3 Assignment Based on HC Emissions

Type	Route	Volume (v/h)	Rate (g/v)	Travel Time (s)	Total (kg)
SO	1	5166	0.0748	102	0.514
	2	2834	0.0448	96.3	
UE	1	3904	0.0762	82	0.61
	2	4096	0.0762	218	
SE	1	3951	0.0762	82	0.602
	2	4049	0.0743	211	

Table 5.4 compares the total CO and HC emissions when different routing strategies are implemented in the traffic assignment model (i.e. UE, SO and SE assignment based on minimizing CO and HC emissions). Also indicated in the table is the percentage differences in the total system costs when the SE and UE assignment are compared with the SO assignment for the indicated pollutant at the left hand side of the table. The results of the assignment show that the increase in total CO emissions when traffic is routed from either UE or SE principles are approximately 17% higher than from the SO assignment. Similar trends are also found in the total HC emissions where the percentage increase in HC emissions for the UE and SE assignment is on the order of 18%. This pattern indicates that the link flow results of the UE and SE assignment are similar for CO and HC objectives.

Furthermore, it is shown in the table that the CO emissions are lower by 0.3% if the objective is an SE_CO rather than an SE_HC assignment. This follows a similar pattern as to the UE assignment where the CO emissions were lower if the objective was to actually charge the drivers for CO production rather than charging the driver for HC production.

However, it is found that the HC emissions are higher by 1% for the SE_HC assignment than the SE_CO assignment. This is also analogous to the UE solution where higher HC emissions were produced if the drivers are charged for their HC emissions rather than being charged for their CO emissions. Therefore, the objective of reducing HC emissions with ITS technologies from either a UE or SE perspective may in fact increase the overall HC emissions on the network.

Table 5.4 - Comparison of System Costs Based on Different Traffic Assignment Objectives

		Traffic Assignment Objective	
		CO	HC
Total CO Emissions (kg/h)	UE	7.14 (17%)	7.27 (19%)
	SO	6.088 (Base)	8.19 (34.5%)
	SE	7.10 (17%)	7.12 (17%)
Total HC Emissions (g/h)	UE	599.4 (17%)	609.7 (19%)
	SO	513.6 (0.02%)	513.5 (Base)
	SE	596.6 (16%)	602 (17%)

Furthermore, Table 5.5 illustrates the difference in total system travel time on the network based on the different environmental objectives and assignment principles. It is shown in the table that the difference in travel time for the SO_TT, SO_CO and SO_HC assignment is less than 0.5%. It is also shown that the overall link travel time difference between the UE and SE assignment for CO emissions is on the order of 1%. Similarly, the difference in travel time based on a UE or SE assignment for HC emissions is 2.4 %. However, the link travel times increase by approximately 49% when the objective is to ensure either CO or HC emissions are equal on both routes (i.e. SE assignment) rather than ensuring that the pollutant emissions are minimized on the entire network (i.e. SO assignment). In terms of travel time on the network, it is shown that the implementing route guidance technologies to obtain equitable measures is similar to an assignment where the drivers minimize their own rate of pollutant production. It should also be noted that the increase in overall link travel times on the network from the SE or SO solution generates an unstable solution because the drivers would normally route themselves to minimize their own travel time. ITS technologies would therefore be needed to influence the drivers on their route choices such that environmental and equity objectives may be achieved on the system.

Table 5.5 Total System Travel Time Based on Different Traffic Assignment Objectives and Principles

Total Travel Time	Traffic Assignment Objective		
	TT	CO	HC
UE (veh-hours)	223.0	325.1	336.9
SO (veh-hours)	222.0	222.3	222.2
SE (veh-hours)	(NA)	322.0	327.8

5.4 System Equitable Traffic Assignment for the University Network

In the previous chapter it was shown that closing Keillor Road which may be considered an equitable measure, increases the overall pollutant emissions by approximately 2% on the network. This section analyzes the effects that ITS technologies may have on the University network when the pollution levels on Keillor Road and 114 Street are equal. This particular example was chosen because of the interests generated from the residents and users of 114 Street by the recent closure of Keillor Road.

The SE assignment analysis is an extension to Chapter 4. In this section, the vehicles on the network are assigned based on an equitable assignment for the different environmental objectives (i.e. fuel consumption, CO and HC emissions) using an incremental assignment model. The total system travel time, fuel consumption, CO and HC emissions based on a UE, SO and SE assignment for each environmental objective are compared. This is then followed by analyzing the total fuel consumption, CO and HC emissions on 114 Street and Keillor Road.

5.4.1 Analysis of Aggregate Costs on the University Network

Table 5.6 illustrates the total system travel time, fuel consumption, CO and HC emissions when drivers are assigned to a route from a UE, SO and SE point of view. Also shown in the table is the percentage differences in the total travel time and pollutants when the SE assignment is compared with the SO assignment. The table indicates that the difference in the system travel time and pollution levels is on the order of less than 0.5% if different objectives are used in the SE assignment. The fact that the pollution levels are similar given any assignment objectives implies that implementing a route guidance system to achieve a SE_HC or SE_CO will generate the same amount of CO emissions on the network.

The table also indicates that if the drivers are routed to ensure that the fuel consumption levels on 114 Street and Keillor Road are equal, the overall fuel consumption is actually higher than the fuel consumption results of a SE_CO or SE_HC assignment. Conversely, it is also shown that the opposite trend occurs for CO and HC emissions. For example, it is shown that the total CO emissions are the same for a SE_CO and SE_HC assignment.

It is also indicated in the table that the system travel time and pollution levels are higher for the SE assignment than if traffic is routed from a UE or SO perspective. The increase in travel time is on the order of 1.9% where the reference condition is the average results from the three assignment objectives based on a SO condition. Furthermore, the increase in total fuel consumption, CO and HC emissions is 1.07%, 0.97% and 1.06%, respectively. This increase in pollutant emissions is significant considering that ITS technologies have been found to generate system improvements that are on the order of less than 7%.

In this example where ITS technologies are implemented to allow Keillor Road to remain open, the overall pollution levels actually increase on the network when equity is examined. Therefore, closing roadways for equity reasons, as shown in Chapter 4 where the increase in pollution levels was on the order of 2% is similar to keeping the roadway open but assigning the traffic to ensure that the pollution levels are equal on adjacent streets.

Table 5.6 Total System Costs Based on Different Traffic Assignment Principles

		Traffic Assignment Objective		
		Fuel	CO	HC
Total System Travel Time (veh-hours)	UE	2273.1	2266.1	2268.4
	SO	2257.9	2256.2	2256.8
	SE	2303.0	2297.2	2297.6
	%	(2.00%)	(1.82%)	(1.81%)
Fuel Consumption (gal/h)	UE	2004.7	2003.1	2003.4
	SO	2001.7	2001.4	2001.5
	SE	2021.4	2020.8	2020.7
	%	(0.98%)	(0.97%)	(0.96%)
CO Emissions (kg/h)	UE	44.47	44.42	44.44
	SO	44.38	44.37	44.37
	SE	44.87	44.84	44.84
	%	(1.10%)	(1.06%)	(1.06%)
HC Emissions (g/h)	UE	3706.4	3702.5	3703.4
	SO	3698.8	3698.1	3698.4
	SE	3738.7	3736.8	3736.7
	%	(1.08%)	(1.05%)	(1.04%)

5.4.2 Route Analysis

Table 5.7 shows the CO emissions on 114 Street and Keillor Road based on the different traffic assignment objectives and principles. Also indicated in the table is the percentage increase or decrease in the total costs on 114 Street and Keillor Road when a SE assignment is compared with a SO assignment. It is shown in the table that the average increase in CO emissions is 46% on Keillor Road based on a SE assignment. However, for the people living adjacent to 114 Street, it is found that they would be exposed to less CO emissions than if the assignment is based either from a UE or SO perspective. The average decrease in CO is approximately 15%. This implies that if a route guidance system is used to route traffic to ensure equal pollution levels on two or more streets, CO emissions may actually increase on some streets or decrease on other streets as indicated in the table.

Table 5.7 - Total CO Emissions on 114 Street and Keillor Road

		Traffic Assignment Objective		
		Fuel	CO	HC
114 Street (kg/h)	UE	3.019	3.003	2.980
	SO	2.744	2.789	2.712
	SE	2.361	2.328	2.285
	%	(-14.0%)	(-16.5%)	(-15.7%)
Keillor Road (kg/h)	UE	1.588	1.568	1.578
	SO	1.607	1.615	1.607
	SE	2.377	2.327	2.285
	%	(47.9%)	(44.1%)	(42.2%)

Furthermore, Table 5.8 illustrates the trends on HC emissions on 114 Street and Keillor Road. It is found in the table that a SE_HC generates the lowest HC emissions on 114 Street when compared to the other objectives such as SE_F or SE_CO assignment. Similar, to the above trends found for CO emissions, the total reduction in HC emissions on 114 Street is on the order of 15% over all the objectives. It is also indicated in the table that HC emissions actually increase by approximately 44% when a SE assignment ensures that Keillor Road has the same emissions as on 114 Street. The increasing trend in HC emissions on Keillor Road implies that implementing a route guidance system to achieve a SE objective that does not involve closing the roadway, actually makes the HC emissions worse.

Table 5.8 - Total HC Emissions on 114 Street and Keillor Road

		Traffic Assignment Objective		
		Fuel	CO	HC
114 Street (g/h)	UE	250.9	249.6	247.7
	SO	228.2	231.7	225.6
	SE	196.4 (-13.7%)	193.7 (-16.4%)	190.2 (-15.7%)
Keillor Road (g/h)	UE	132.2	130.5	127.9
	SO	133.7	134.4	133.7
	SE	197.5 (47.7%)	193.4 (44.6%)	189.9 (42.0%)

Finally, Table 5.9 illustrates the total fuel consumption on 114 Street and Keillor Road based on the different traffic assignment principles and objectives. Although direct benefits to the residents along Keillor Road or 114 Street are not foreseen by ensuring that fuel consumption levels are equal, the results are tabulated because fuel consumption is directly related to pollutant emissions. Therefore, indirect benefits may be found if route guidance systems are used to ensure that fuel consumption levels on Keillor Road and 114 Street are equal.

The table indicates that if the people living adjacent to Keillor Road want to ensure that the fuel consumption level is the same as on 114 Street, they would actually indirectly receive higher pollution levels than if drivers or system operators found routes based on UE or SO assignment principles. The average increase in fuel consumption on Keillor Road is on the order of 45%. Conversely, the people living adjacent to 114 Street would be exposed to fewer pollutant emissions if a system equitable approach is applied in the routing strategies to ensure that fuel consumption levels are equal. The average decrease in fuel consumption on 114 Street is 16% where the reference is the fuel consumption results based on a SO assignment. It is also noted in the table a SE_F generates the lowest overall fuel consumption levels when compared to the SE_CO and SE_HC assignment.

Table 5.9 - Total Fuel Consumption on 114 Street and Keillor Road

		Traffic Assignment Objective		
		Fuel	CO	HC
114 Street (gal/h)	UE	134.5	133.8	132.8
	SO	122.5	124.4	121.1
	SE	102.1	104.2	102.3
	%	(-16.7%)	(-16.2%)	(-18.4%)
Keillor Road (gal/h)	UE	71.03	70.15	70.59
	SO	71.88	72.26	71.88
	SE	101.6	103.5	101.6
	%	(41.3%)	(43.2%)	(41.3%)

5.5 Conclusions

1. The incremental assignment technique does not require a convex generalized cost function. It was shown that the incremental algorithm could be used as a means to overcome the limitations of the traditional user equilibrium assignment model. A simple two link example illustrated that the incremental technique could produce reasonable results when compared to an analytical solution that routed traffic based a non-convex noise pollution function, multiple user classes, and equity objectives.

2. It was shown in a simple two link network that routing traffic to achieve "environmental" equity measures resulted in similar link flows and overall pollution levels as a UE assignment that minimized the users pollution production.

3. It is found that implementing a SE assignment on the University network generates an increase in the total pollutant emissions of 1.1% when the drivers had the option of using Keillor Road but with the objective of ensuring equal pollution levels on Keillor Road and 114 Street. Therefore, implementing a route guidance system to achieve equitable

measures is similar to closing the roadway (another equitable measure) where it was found that the total pollution levels increased by 2% when Keillor Road was closed.

4. In the University example where the traffic was assigned on the network to ensure that equal pollution levels existed on 114 Street and Keillor Road, it was found that using route guidance systems to explicitly route traffic from an equitable perspective actually increased the pollution levels by 44% on Keillor Road when compared to an assignment where the drivers were routed from UE or SO assignment. Similarly, it was found that the pollution levels on 114 Street decreased on the order of 16% based on a system equitable assignment.

Chapter 6 - The Effect of Toll Charges Traffic Assignment

6.0 Introduction

Since the 1800's toll roads have been used throughout the United States in order to pay for the cost of building and maintaining sections of their roadway network. Canadians have also used toll fares along bridge links such as in Halifax, Nova Scotia. The use of toll roads dropped in 1940's because government agencies took over the cost of highway infrastructure building. However, toll charges are returning as an alternate source of funding due to the continuous reduction in funds from government agencies for transportation projects and the need to mitigate traffic congestion. Highway 407 in Toronto which is presently under construction is proposed to be a toll highway which will use the newest automated vehicle identification system technology (AVI).

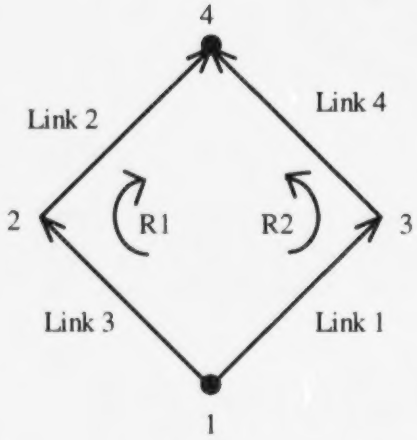
With the advances in ITS technologies, the use of electronic toll collection systems will allow transportation engineers to use tolls to achieve other objectives such as reducing traffic congestion and air pollution. In the previous chapters, it was implied that routing traffic in order to achieve reductions in vehicular pollution would involve charging the drivers based on the amount of pollutants they emitted or by explicitly routing the traffic through a centralized route guidance system. This chapter examines how the same objectives presented in the previous chapters may be obtained through toll charges.

The University network will be used as the test bed where a toll charge will be implemented on Keillor Road. It was found in previous chapters that pollution levels on 114 street, for example, are reduced if drivers have access to Keillor Road. However, if Keillor Road is open, there is a cause for concern from the residents that live adjacent to Keillor Road due to the increase in pollutant emissions.

This chapter first examines the effect of adding a toll charge on a small network. The well-known example network where the Braess paradox exists is used to describe the effects on system travel time as well as on link flows when a toll is introduced. Second, the link flows, system travel time and environmental costs are compared if a toll is introduced on Keillor Road in the University network.

6.1 Brief Description of the Braess Paradox

A sample network used to illustrate the Braess paradox is divided into two sections: A base network that has two defined routes and an extended network that has three routes. The base and extended network are shown in Figures 6.1a and 6.1b. The base network is a symmetrical network where links 1 and 2 represent freeway links that have high capacities and long free flow travel times. Links 3 and 4 represent shorter arterial links or local streets with lower capacities and free flow travel times. The capacity on links 1 and 2 is 10000 v/h with free flow travel times of 36.7 minutes, whereas, the capacity on links 3 and 4 is 2000 v/h with free flow travel times of 16.6 minutes.



Note: R1 = Route 1
R2 = Route 2
R3 = Route 3

Figure 6.1a - Base Network

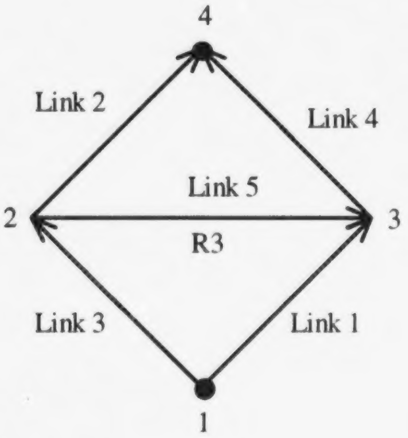


Figure 6.1b - Extended Network

The extended network has an additional low capacity arterial link that connects nodes 2 and 3 as shown in Figure 6.1b. This "superlink" has a capacity of 1800 v/h and a free flow travel time of 13.4 minutes. The extended network represents a situation where drivers are aware of an alternative route (i.e. route 3 which consists of links 3, 5 and 4) through a neighbourhood but must pay for the use of that route. Based on free flow travel times, the alternate route is shorter, however, due to the low capacity and additional cost, route 3 may not always be the best alternative.

A version of the standard Bureau of Public Roads travel time function shown in Equation 2.1 is used as the generalized cost function to analyze the network in the traffic assignment problem. In the example problem, the parameters $\alpha = 1$ and $\beta = 1$.

The Braess Paradox example is well documented in literature. It has been shown by the Braess paradox that the overall system travel time and individual user travel time may both increase when a link is added to an existing system. (Braess, 1968, Stewart, 1980). In essence, the increase in travel time on the extended network occurs because drivers want to minimize their own travel time. In previous work, (Rilett, 1992) it was illustrated that the Braess paradox exists even under realistic travel time impedance functions. Furthermore, it was shown that the paradox is flow dependent. At low O-D demand rates, for example, an additional link or improvement to the system will not result in the Braess paradox. There will exist a net decrease in link travel time or system travel time when the drivers route themselves to minimize their own travel time on the network. However, for higher demand rates, it was found that the improvements to the network will actually increase overall link travel times.

The following paragraphs illustrate the Braess paradox when the addition of a new link is known by the users on the network shown in Figure 6.1b. In this example, the UE and SO assignment models that minimize route travel time is examined when no additional tolls are implemented on the new alternate route (i.e. route 3). It is assumed that the origin destination demand is 600 v/h from node 1 to 4. From the above information, Table 6.1 shows the route flows as well as the total system travel time for the base and extended network.

Table 6.1: Route Flows and Total System Travel Time for the Base and Extended Network

Network	Type of Assignment	Route	Route Flow (v/h)	Total System Travel Time (veh-hours)
Base	User	1	300	569
		2	300	
Base	System	1	300	569
		2	300	
Extended	User	1	90	
		2	90	579
		3	420	
Extended	System	1	222	
		2	222	564
		3	156	

From the above example, there are a few important points that should be noted. First, the route flows are the same for both the UE and SO assignment in the base example due to the symmetrical nature of the network. This results in the same total system travel time of 569 veh-hours for the user equilibrium and system optimal assignment.

It is also shown in Table 6.1 that the addition of a link does not guarantee an improvement to the total network travel time and individual link travel time from a user point of view. The average travel time on a route from a UE assignment increased from 56 minutes for the base network to 59 minutes for the extended network. The total travel time savings dropped by 10 veh-hours for the extended network which leads to a percentage increase in total system travel time of approximately 1.75%. The increase in total system travel time is due to the increase in the number of vehicles that use route three as their new alternative.

There are some potential benefits to the average travel time and total system travel time for the extended network if the assignment is based on a system optimal principle. If the drivers were explicitly given their routes by a centralized route guidance system, the number of vehicles on route three would decrease by 63%. However, the total network travel time savings is on the order of less than 1%.

6.2 Toll Charge

In the previous example, the travel time impedance function was the same on all links. However, route 3 on the extended network may be considered to be an arterial route that is not meant for through traffic. Drivers that choose to use route 3 as their alternate route are placing an additional burden to the neighbourhood and this negative result may be incorporated into the generalized cost function by adding a cost or toll charge to the travel time impedance function. In this example, the generalized cost function for link 5 includes the travel time that the drivers experience on the link plus a toll charge which is proportional to the drivers mean value to time subject to a distribution about the mean (Leurent, 1994). Equation 6.1 illustrates the modified BPR function that is used to analyze link 5.

$$t_i = fft_i(1+\frac{V_i}{c_i})+\frac{P_i}{v} \tag{6.1}$$

Where:

ti = Travel time on link i (h)
fft_i = Free flow travel time on link i (h)
V_i = Volume on link i (v/h)
c_i = Capacity on link i (v/h)
P_i = Cost of using link i (i.e. Toll Charge) ($/v)
v = Value of time, VOT ($/h)

The toll charge, for example, may include factors such as the additional noise levels or pollutants emitted as the volume on the route increases. Other costs that could be incorporated into the toll charge may include, the cost of maintaining and operating that roadway, the cost of providing noise barriers, home insulation or even costs to the general improvements of the neighbourhood. The users that choose route 3 will therefore assess their choice based on the toll charge as well as how much they value their time.

In the example, it is assumed that the users' value of time (VOT) may be represented as a lognormal distribution where the variation of the VOT is based on an average income distribution of each origin-destination pair. The VOT, in this example, is assumed to have a median value of $10 per hour with a standard deviation of its natural logarithm of 0.6. It is assumed that the system operators can vary the toll charge on link 5 from $0 to $3 per vehicle. The change in toll represents a situation where system operators have control on how much to charge the users depending on the time of day and the amount of pollutants emitted in the area. In the example, it should be noted that the O-D demand is fixed: users do not have the option of not making the trip. However, the users do have the option of switching routes and the effect of varying the toll charge on the alternate route is examined.

The main purpose of this example is to answer the following questions: 1. What happens to the total system travel time if a toll charge is introduced on a section of route 3 (i.e. link 5)? 2. What happens to the link flows and total system travel time if the value of time for each individual user or O-D pair is random as opposed to constant? 3. Does the Braess paradox still exist when a charge is included on the additional link in the network? 4. What happens to all of the above questions if the demand rate is varied? The following section is an attempt to answer these questions.

The analysis is based on the UE assignment model where Equation 2.1 represents the generalized cost function for routes 1 and 2 and Equation 6.1 represents the generalized cost function for route 3. Only the UE assignment is examined due to the fact that drivers are more likely to route themselves in order to minimize their own generalized cost and will not likely take the advice from a system operator because of the toll charge already implemented by the system operators on route 3. Consequently, a toll charge implies that people will choose their own routes to minimize their own travel time on the network. In the previous chapters traffic routing from a SO perspective was used as a reference and in the examples presented it was assumed that a centralized route guidance system would be available to route traffic not only to minimize link travel times but to minimize environmental costs as well. In this chapter, the reference is the UE assignment solution when the toll is zero dollars.

6.2.1 Analysis of the Toll Route for the Sample Network

A list of the steps used in the analysis of toll charges in traffic assignment modelling for the sample network is shown below:

1. The demand rate is varied from 200 v/h to 1000 v/h in increments of 200 v/h.

2. The total system travel time and link flows for each demand rate are determined based on UE principles.

3. The changes in flow on link 5 (i.e. route 3) for each toll charge is plotted.

4. The variation in flow on link 5 (i.e. route 3) is illustrated when the VOT is random and constant.

5. The total system travel time for the extended network where the VOT is random and constant is compared with the base condition for each toll charge.

The following analysis generated two sets of graphs. The first set of graphs illustrates the change in link flow with respect to the increase in cost from zero dollars to three dollars on link 5. Figure 6.2 shows the change in link flow on route 3 with respect to the toll charge for a demand level of 200 v/h from node 1 to 4. At this demand level and when all the drivers perceive the same value of time (i.e. constant value of time), the total flow of 200 v/h on link 5 remains constant until the toll reaches 60 cents. When the toll charge is between 60 cents and $1, the link flow decreases linearly from 200 v/h at a toll of 60 cents to approximately 20 v/h at a toll of $1. If system operators introduce a toll greater than $1 on link 5, link flows are essentially 0 v/h which indicates that all of the drivers no longer find any travel cost benefits on route 3. This link flow pattern is analogous to a "real world" situation where a new driver in the area would not know about the existence of an alternate route.

The example illustrated in Figure 6.2 where the value of time for all the drivers is constant, indicates that link flows may be over or under estimated for different toll charges when compared to the case where the drivers' value of time is represented by a lognormal distribution (i.e. random). Figure 6.2 shows that at toll charges under 80 cents and when the drivers are subject to a random value of time, link flows on route 3 change gradually as the toll increases. It is also shown that not all the drivers choose route three as the increment of the toll increases whereas if all the drivers had a constant value of time, route 3 would be the best alternative up to a toll of 60 cents. Point a on the graph indicates the toll charge where the link flows are the same for the constant and random case. Past point a, or at higher toll charges, link flows on route 3 for drivers that perceive different values of time, never reach 0 v/h which indicates that some drivers perceive route three as the best alternative even at high toll charges.

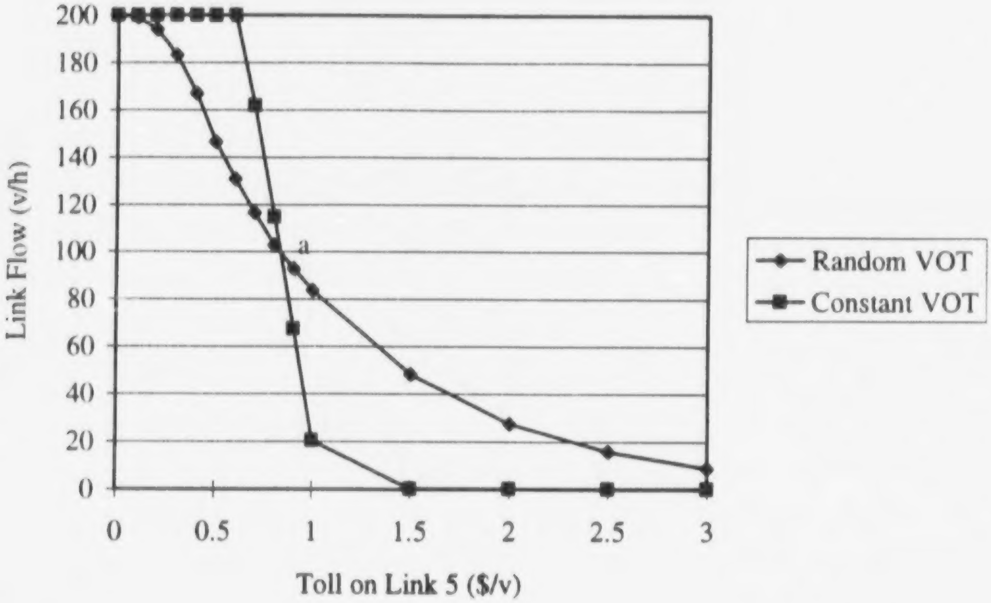


Figure 6.2 - Changes in Link Flow as the Cost on Link 5 Increases for a Demand Level of 200 v/h

At higher demand levels as shown in Figure 6.3 where the demand rate is 600 v/h, the rapid linear drop in link flow on link 5 at a toll charge less than $1 still exists when drivers are subjected to a constant value of time and change in toll charge. Point a in Figures 6.3 indicates when the link flow reaches 0 v/h on route 3. Figures 6.3 also shows that the rapid drop in link flows in the case where the value of time is a lognormal distribution is less noticeable. It is also shown on the graph that link flows on route 3 for the random and constant case are approximately the same until the toll is 40 cents. Point b in Figure 6.3 indicates the point of divergence in link flows between the constant and random case. When the value of time is represented by a lognormal distribution, it is shown that the link flows on route 3 are higher than for the case where the value of time is constant. Similar to the demand level of 200 v/h, the flows on link 5 when the demand rate is 600 v/h never reach 0 v/h as the toll increases to a value of $3 on the link.

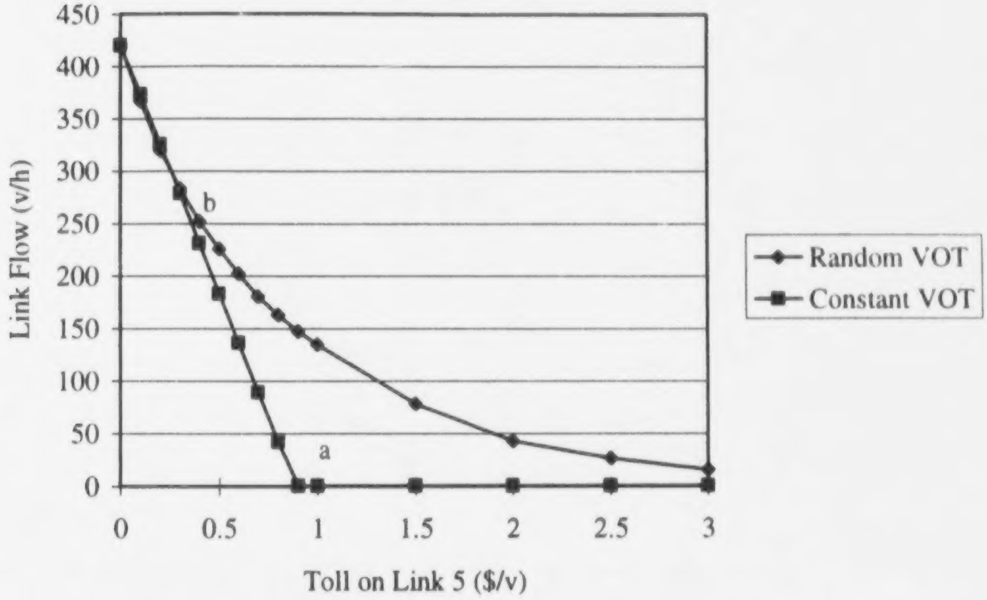


Figure 6.3 - Changes in Link Flow as the Cost on Link 5 Increases for a Demand Level of 600 v/h

At a demand level of 1000 v/h, as shown in Figure 6.4, link flows on route 3 are always higher for drivers that are subjected to a random value of time. Similar to the previous examples, some drivers will always find route 3 as the best alternative even at high toll charges. Moreover, if the value of time is constant, the drivers will find that route 3 is no longer a feasible alternative when the toll is 80 cents. At this toll, all drivers chose to use the freeway/arterial combination route - Alternatives one and two.

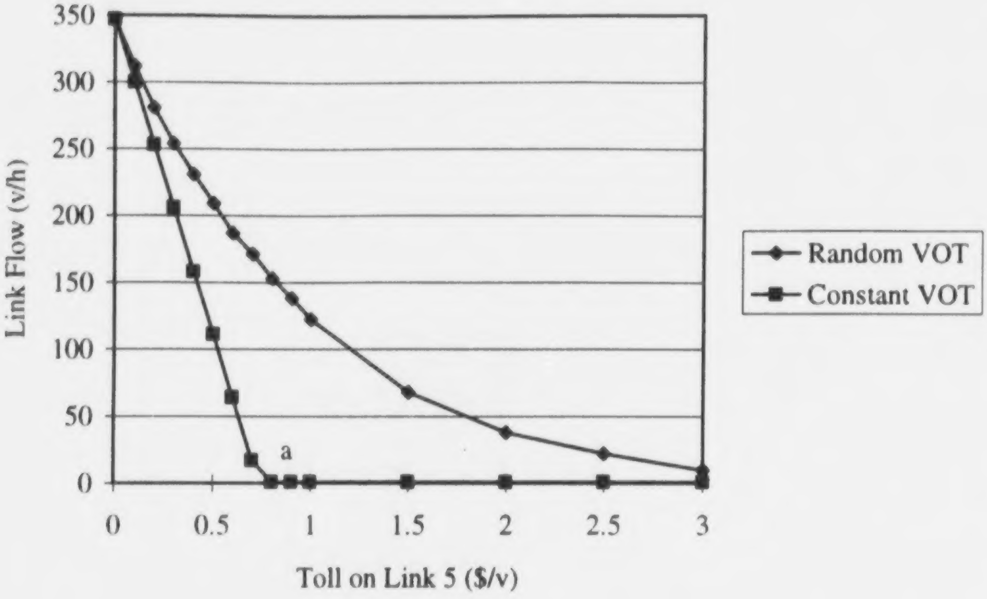


Figure 6.4 - Changes in Link Flow as the Cost on Link 5 Increases for a Demand Level of 1000 v/h

The next set of graphs illustrate the change in system travel time with increase in toll charge on link 5. The three lines as shown on the legend in the figures indicate the system travel time for the base case and extended network as the toll increases.

In earlier research, it was found that the increase in total system travel time for the extended network is dependent on the demand level (Rilett, 1992). Figure 6.5 illustrates that at a demand level of 200 v/h, the addition of a link creates an overall travel time improvement of 6% on the network when the drivers do not have to pay for the use of route 3. Similarly, if link 5 has a toll charge of less than 60 cents, the overall system travel time improves by 11 veh-hours or 6% where the reference point is the total system travel time for the extended network when system operators do not implement a toll charge. System travel time savings still exist at toll charges between 60 cents and $1.50 However, when the toll reaches $1.50, the addition of the link does not generate any overall system travel time improvements. This pattern implies that drivers do not find that the existence of the new link can generate any improvements to their own generalized costs and they no longer use route 3 as an alternative.

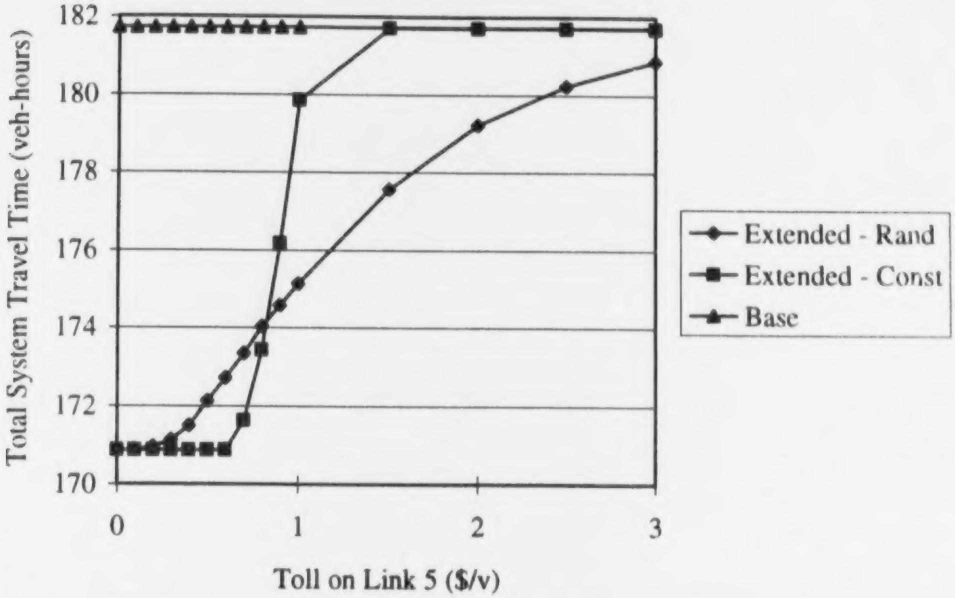


Figure 6.5 - Changes in Total System Travel Time with Increase in Cost on Link 5 for a Demand Level of 200 v/h

Furthermore, if the O-D pair is 200 v/h and the value of time is a lognormal distribution (i.e. random), the system travel time will increase at a more gradual rate but will never reach the system travel time recorded in the base example for the indicated toll range as shown in Figure 6.5. It is also important to note that a random value of time generates a higher total system travel time for a toll charge less than 90 cents than for the case where the value of time is constant. Moreover, if the drivers' value of time is random and if the demand level is low (i.e. a demand of 200 v/h), the extended network will always be more efficient even if a toll charge of $3 is introduced on link 5.

It was already mentioned previously in the first example that if the demand level is 600 v/h and the drivers route themselves to minimize their own generalized costs which is not subject to any supplementary costs such as a toll, the addition of a new link will actually increase the user and overall system travel time (Braess, 1968). Figure 6.6 illustrates that the total system travel time for the extended network increases from 569 veh-hours to 579 veh-hours or 1.75% when the drivers do not pay for the use of route 3. However, by introducing a toll charge, there exists a reversal where the total travel time on the network improves if the drivers know about the existence of the new route. For example, Figure 6.6 illustrates that if the toll is 30 cents, the overall system travel time improves from 569 veh-hours for the base network to 567 veh-hours for the extended network. The total system travel time reaches a minimum of approximately 564 veh-hours at toll charges of 60 cents in the constant case and 80 cents for the random case. This results in an overall travel time improvement of 2.6% where the reference is the total travel time on the network when drivers did not have to pay for the use of route 3 on the extended network. Therefore, if a toll is introduced, drivers that do not value their time as much as other drivers will use route 3.

The relationship between the introduction of a toll charge on a new link and improvement to the system is dependent on whether the value of time is random or constant. An O-D pair that has a constant value of time will generate overall improvements to the system travel time within boundary toll charge conditions. At a demand level of 600 v/h, for example, the overall system travel time improvements occur when the toll is between 30 and 90 cents with an optimal travel time savings at a toll charge of 60 cents. However, if all the drivers have the same value of time and the toll charge is high, they will stop using route 3 because the drivers perceive that the additional cost on the link will not generate any user benefits.

An O-D pair subject to a random value of time will always generate system travel time improvements on the extended network even when the toll charge is at the maximum rate set in the example (i.e. $3). In the example illustrated in Figure 6.6, system travel time improvements still occur when the toll is $3. However, the graph also indicates that as the toll increases on the extended network, the total system travel time approaches the travel time experienced in the base example. Therefore, tolls greater than $3 will result in more (or all) drivers choosing routes 1 and 2 to get to their destination.

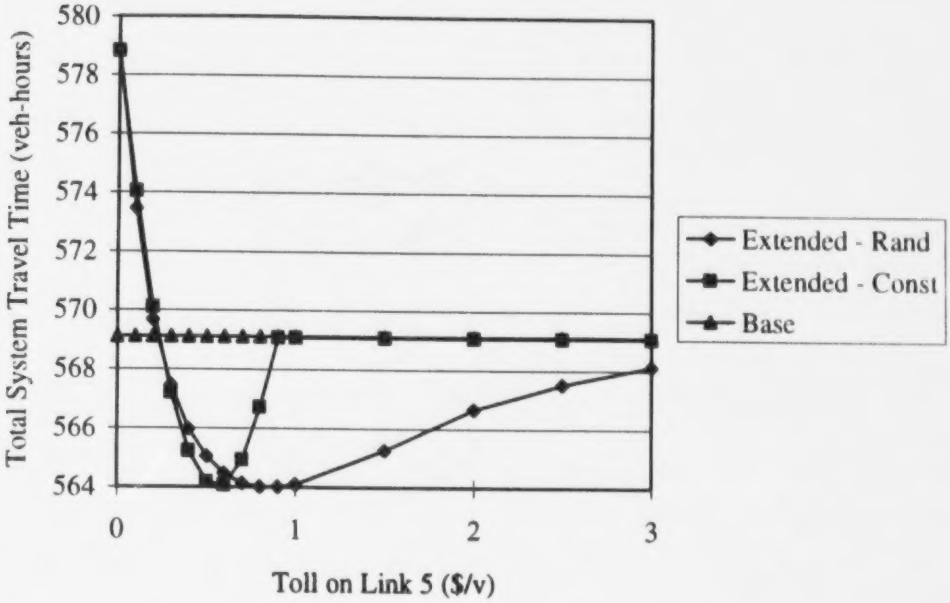


Figure 6.6 - Changes in Total System Travel Time with Increase in Cost on Link 5 for a Demand level of 600 v/h

Similarly, Figure 6.7 shows the change in system travel time for a demand level of 1000 v/h as the toll charge increases on link 5. This figures illustrates clearly that the range in total system travel time improvements is limited for an O-D pair with a constant value of time. The total system travel time savings on the extended network occurs at toll charges between 40 to 70 cents for the constant case whereas overall system travel time savings exist between 80 cents and $3 in the random case. Furthermore, the total system travel time savings is on the order of 1.5% for the random and constant cases given that the reference is the travel time on the extended network before any tolls are implemented on the network.

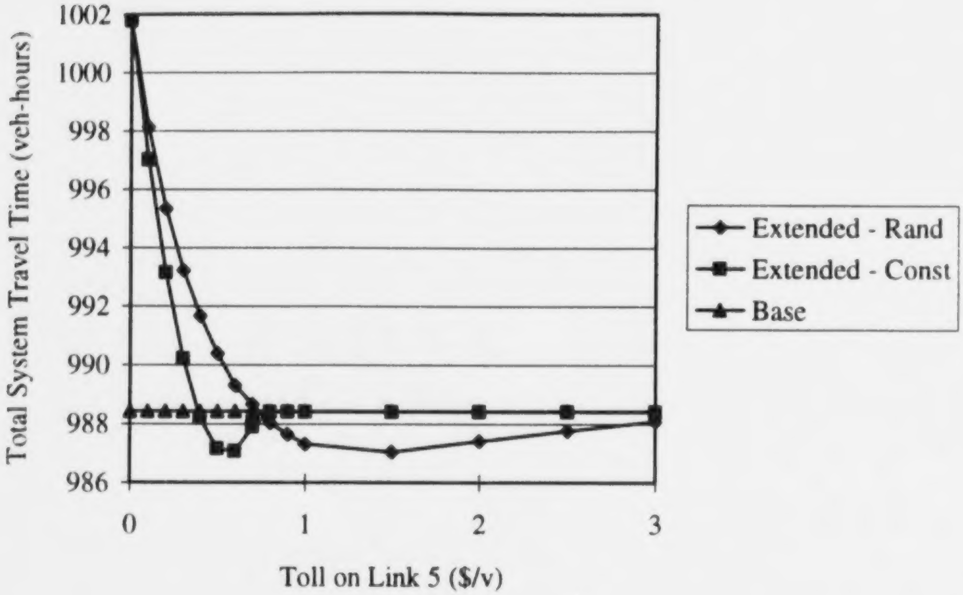


Figure 6.7 - Changes in Total System Travel Time with Increase in Cost on Link 5 for a Demand Level of 1000 v/h

Although system travel time improvements are small, the examples only represent a theoretical case that illustrate what might happen if either improvements to the network and/or toll charges are introduced to the system. In the examples, overall travel time improvements for the extended network where the reference is the system travel time at a cost of zero dollars are within 1-3%. These values are reasonable considering that other research work in traffic management yield similar travel time improvements. In ITS research where congestion management is the main objective, travel time improvements are less than 7 % (King and Mast, 1987).

6.3 The Effect of Introducing a Toll on Keillor Road

It was shown in Chapter 4 that the effect of adding Keillor Road to the University network improved the fuel consumption and pollution levels on 114 street by approximately 19% on average. However, pollution levels on Keillor Road increased on the order of 90% when Keillor Road remained open. Therefore, if Keillor Road is to remain open to the general public, it may be feasible to charge for the amount of pollutants emitted in the area.

This section analyzes the effects of a toll charge on the University network. The link flows and environmental costs on Keillor Road and 114 Street as well as the overall system travel time, fuel consumption, CO emissions and HC emissions are compared with the increase in toll on the Keillor Road corridor. It is assumed that the toll charge could range from $0 to $2 along Keillor Road. Electronic toll collection systems could be used to collect vehicular pollutant information at certain points along the corridor. System operators could then set the toll according to the amount of pollution produced. It is also assumed that the drivers will not stop along to corridor to pay the toll and therefore drivers will be required to purchase a "smart card" in order that the toll charge be deducted as the drivers use Keillor Road.

The effect of tolls on Keillor Road is analyzed by assigning the traffic from a UE perspective where the travel time functions shown in Equations 2.1 and 6.1 are used as generalized cost functions. The value of time parameter is characterized in the same manner as in the Braess network example where the median is $10 per hour and a standard deviation of its natural logarithm set to 0.6. The method of successive averages is used to solve the UE assignment where 20 iterations was found to be sufficient to reach an equilibrium solution. Similar to the argument presented in the simple two link example, the SO assignment solution is not presented in this section because it is implied that toll charges will cause drivers to choose their own route to minimize their generalized costs.

6.3.1 Analysis of Link Flows on Keillor Road and Total System Costs

Figure 6.8 illustrates the change in flow in both the northbound and southbound direction with respect to the increase in toll charge on Keillor Road. It is established from the graph that in the a.m. peak hour and when drivers are not charged for the use of the roadway, the northbound and southbound flows are approximately 800 v/h and 200 v/h, respectively. The implementation of a toll charge in the southbound direction does not have any adverse effect on the link flows. The southbound link flow on Keillor Road remains constant at 130 v/h once the toll reaches 50 cents. In essence, the drivers perceive that the increase in travel time caused by the toll charge is still a lower than if the same drivers would use 114 Street to get to their destination.

A toll charge in the northbound direction does, however, have a significant effect on the link flows as shown in Figure 6.8. At a 40 cent toll charge, the link flow on Keillor Road is reduced by one half the original flow to approximately 400 v/h. For toll charges greater than 50 cents, the northbound link flows on Keillor Road continue to decrease. At higher toll charges, the number of vehicles on Keillor Road reach a constant rate of 60 v/h as they travel towards the University area or Downtown. The resulting link flows in the northbound are lower than the flows in the southbound direction for the same toll charge. This decreasing link flow pattern implies that including a toll charge increases the drivers' generalized cost function to a level where Keillor Road is no longer a feasible route. Other routes such as 114 Street become more favourable.

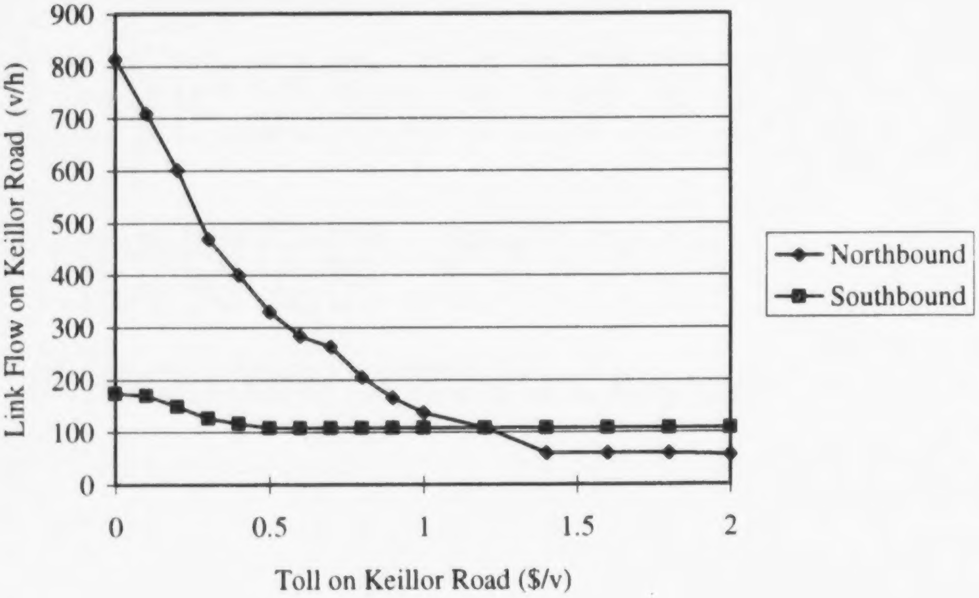


Figure 6.8 - Link Flow on Keillor Road in the Northbound and Southbound Direction as the Toll Charge Increases

The resulting changes in link flows on Keillor Road with increase in toll charge also affects the trends in the total system travel time, and total fuel consumption, CO and HC emissions. Figure 6.9 illustrates the percentage increase in total system travel time, fuel consumption, CO and HC emissions as the cost on Keillor Road increases. It is indicated on the graph that the effect of the increase in toll is similar for all system costs on the network. This is shown by the fact that the percentage increase in the total fuel consumption and HC emissions, for example, is less than 0.2% for the same toll range.

The increase in total system travel time and total system environmental costs is linear as the toll ranges from 0 to 60 cents. The increasing trend is noticeable for tolls greater than 60 cents, however, the overall system costs increase at a slower rate. When the toll reaches a $1.50, the increase in the overall system costs remains constant where the total system costs increase by approximately 1.9% given that the reference is the cost on the network when drivers do not pay for the use of Keillor Road. Figure 6.9 also indicates that when the toll is too high, drivers will use other routes and the use of Keillor Road will generate very little system improvements. In essence, the aggregate pollutant increase of 1.9% is the same as the percentage increase in pollutant emissions found in Chapter 4 when traffic was assigned on the network given that Keillor Road was closed. High toll charges are beneficial for the residents along Keillor Road because drivers from south Edmonton are discouraged from using the roadway. For example, at a toll of $1.50, the link flow on Keillor Road is 60 v/h in the northbound direction which is 93% lower than the case where drivers are not charged for Keillor Road.

Another area that traffic engineers need to examine is whether it is possible with toll charges to obtain the same pollutant emissions levels as those produced from a SO assignment. Because, the analysis is based on a UE assignment and the pollutant emissions on the network increase as the toll reaches $2, it is not possible to gain system benefits when the users choose their own routes given that they must pay a fee on Keillor Road.

It is also be shown from Figure 6.9 that the total pollutant emission increase based on system equitable assignment such as the one presented in Chapter 5 may be found when the toll is 50 cents. At a toll of 50 cents, the increase in pollutant costs is approximately 1.1%. However, the link flows generated at this toll do not result in an equitable assignment where the pollution levels are the same on 114 Street and Keillor Road as will be shown in the next section.

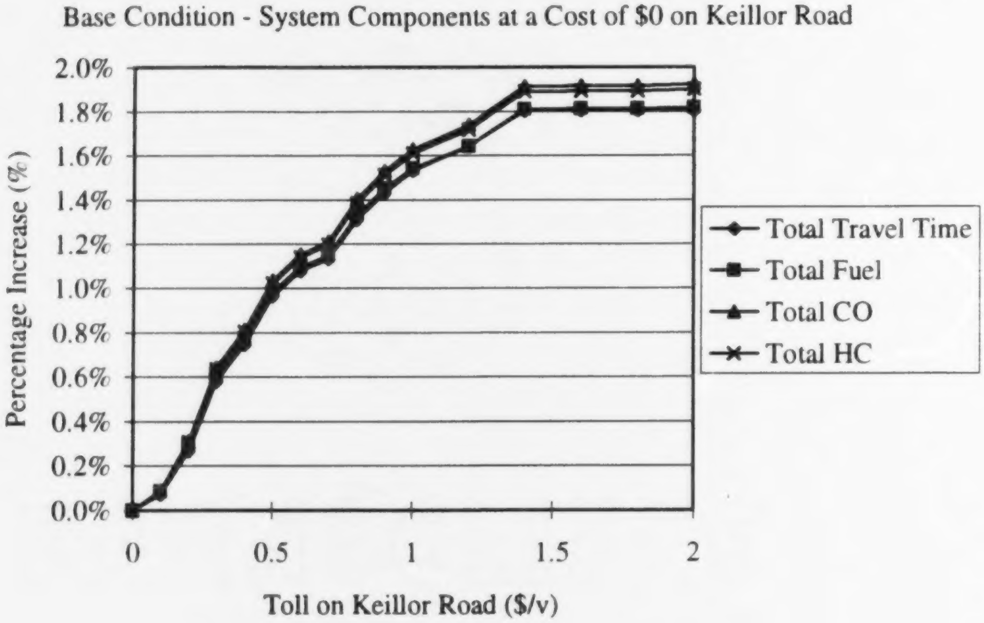


Figure 6.9 - Increase in Total System Costs as the Toll on Keillor Road Increases

6.3.2 Route Analysis

The effect of the toll on Keillor Road can also be examined based on determining the increases or decreases in the total fuel consumed, CO and HC emissions on 114 street and Keillor Road as the toll increases. Figure 6.10 shows the total CO emissions per hour on Keillor Road and 114 street with respect to a toll increase on Keillor Road. Similar trends in the total fuel consumption rate, and HC emissions were found for Keillor Road and 114 Street and they are therefore not shown in this section. As already mentioned in

Chapter 4, the overall distance along the two corridors is similar and therefore the environmental conditions may be compared.

In Figure 6.10, it is shown that the total CO emitted on 114 street from 72 Ave. to 87 Ave. increases from 3 kg/h to 3.5 kg/h while the CO emitted on Keillor Road decreases from 1.5 kg/h at a toll of $0 to 0.4 kg/h for a toll of $2.00. The increasing trend in the rate of CO emissions on 114 Street is caused by the increase in flow as the vehicles are diverted away from Keillor Road as the toll increases. It should also be noted that the total CO emissions on 114 Street are higher than those on Keillor Road due to the large link flows on 114 Street from the "background" traffic generated by other areas in the network that use 114 Street to reach their destination. From the information presented on the graph, it is shown that an equitable assignment where the pollution levels are the same on Keillor Road and 114 Street, cannot be achieved due to the large link flows from "background traffic on 114 Street. A toll on 114 Street would be required in order to reduce the amount of traffic from other areas of the network that use 114 Street.

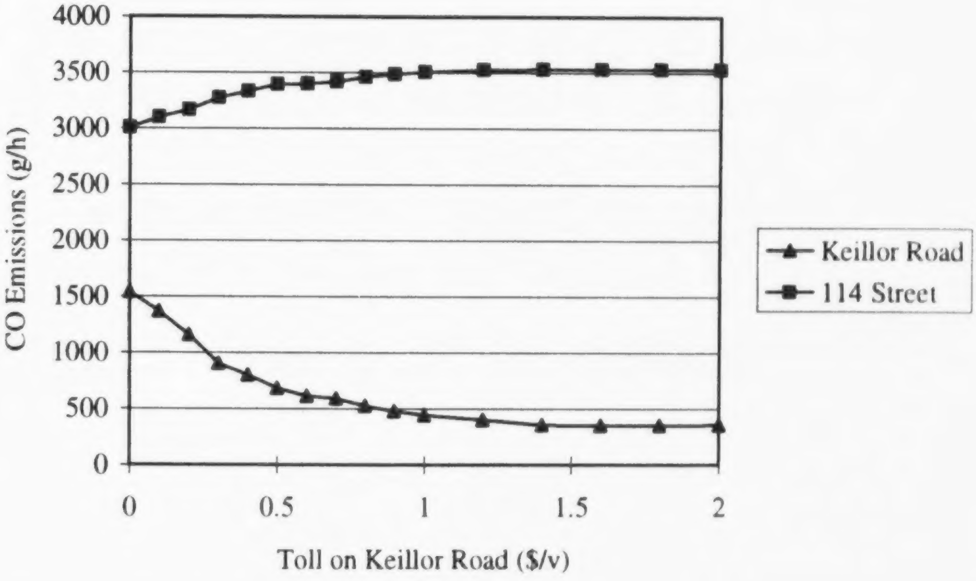


Figure 6.10 - Differences in System Costs on 114 Street and Keillor Road as the Toll Charge Increases

Figure 6.11 summarizes the percentage changes in fuel consumption, CO and HC emissions on 114 Street and Keillor Road. The reference condition is the environmental costs at a toll of $0 on Keillor Road. The graph shows the relative trends in pollutants as the link flows decrease on Keillor Road and increase on 114 Street. Along 114 street between 72 Ave. and 87 Ave., the increase in total pollutants is on the order of 18% as the toll on Keillor Road increases. This increase in pollution levels on 114 Street is similar to an assignment where the drivers do not have access to Keillor Road as shown earlier in Chapter 4. It was shown in Chapter 4 that the increase in pollution levels on 114 Street with Keillor Road closed was on the order of 20% for a UE assignment based on different objectives. At high toll charges, the cost of using Keillor Road increases the travel time on the route which directly reduces the flow and pollution levels on Keillor Road but increases the pollution levels on 114 Street.

The graph also shows that the changes in fuel consumption, CO and HC emissions are directly related to each other as the flows on the route and toll charges change. This pattern is indicated by the fact that all three pollutants are shown by a single line on the graph.

6.3.3 Optimum Toll Charge

The optimum toll charge is also a concern to traffic engineers and government agencies because they want to generate maximum revenues or minimum pollutant emissions as well as maintaining traffic on the streets below capacity. In the following analysis, the optimum toll charge and corresponding revenue is determined based on obtaining minimum overall pollution levels, minimum pollution levels on 114 Street and Keillor Road, and maximum revenues. The revenue per hour may be determined by Equation 6.2.

$$\text{Revenue} = \text{Number of vehicles per hour on the link} * \text{Cost on the link} \qquad (6.2)$$

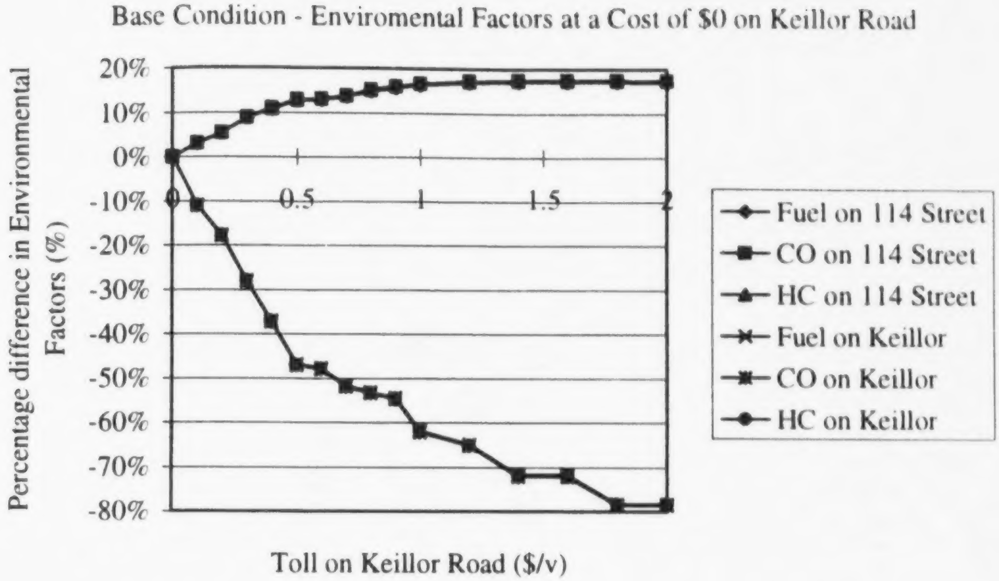


Figure 6.11 - Percentage Difference in Environmental Costs on 114 Street and Keillor Road Based on an Increase in Toll Charge on Keillor Road

An optimum toll charge to ensure that the pollution emissions are a minimum on the entire network does not exist. It is found that the pollutant emissions on the network are a minimum when the toll charge is $0 on Keillor Road. However, from a route perspective, the optimum toll charge would be $1.40 or greater in order to ensure minimum pollution levels on Keillor Road. This leads to a maximum revenue of $ 80 per hour as indicated in Figure 6.12. On 114 Street, the minimum pollutant emissions exists when the maximum number of drivers use Keillor Road and therefore, the optimum toll charge set by the system operators would be $0.

Strictly on a revenue basis, Figure 6.12 illustrates the revenue per hour as the toll charge on Keillor Road increases for both the northbound and southbound direction. In the southbound direction, the revenue per hour continuously increases because the flow on Keillor Road remains constant given any toll charge as shown previously in Figure 6.8. In the northbound direction, revenues reach a maximum at a toll of approximately 70 cents. It should also be noted that once the toll reaches $1.40, the link flows in the northbound direction reach a constant rate which causes a linear increase in the total revenues. This indicates that if the toll is $1.40 or greater the results in the assignment for the northbound direction are meaningless. Even with the high toll charge, some drivers still find Keillor Road as the best option.

The related revenue based on a toll of 70 cents and the amount of vehicles on Keillor Road is $190 per hour. In essence, drivers that use Keillor Road to get to the University area or Downtown would contribute approximately $95000 per year to the improvement of the environment if the dollars received were used strictly for environmental concerns. This value is based on the premise that there are 250 working days in a year and travellers on Keillor Road would contribute in both the a.m. and p.m. peak.

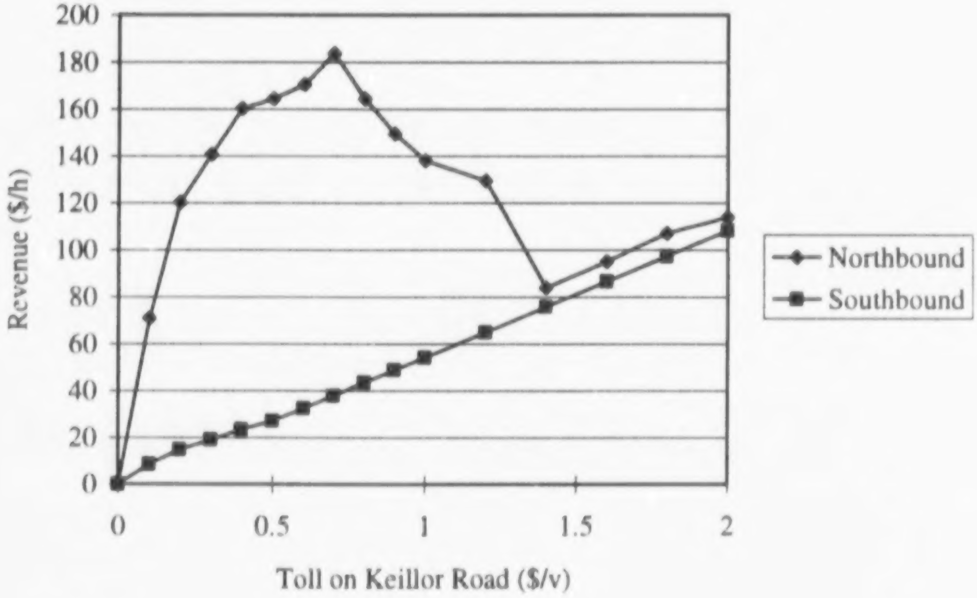


Figure 6.12 - Toll Revenues

6.4 Conclusions

1. Automated toll collections systems could be adapted to include toll charges based on environmental factors. These technologies could easily identify vehicle pollution rates at key points along the network and charge the users on a per rate basis.

2. The example network shows a reversal in the Braess paradox when a toll charge is added to the extended network. The reversal is effective only for certain ranges of toll charges and demand levels. It was shown that an improvement to the overall travel time on the extended network is also dependent of whether the O-D pair is subjected to a constant or random value of time.

3. It was shown that modelling the value of time as a random parameter with a lognormal distribution is an effective way of analyzing the effect of electronic toll collection systems within an urban environment. It was found on the simple network that if the drivers' value of time is represented by a lognormal distribution, the drivers will continue using the new alternate route even at high toll charges due to driver perception error.

4. For the commuters, it may be appropriate for Keillor Road to remain open. However, the increase in vehicular pollution may cause some concerns by the residents adjacent to the roadway. It was found that the overall pollution levels on the network are the same as those generated from a system equitable assignment when the toll is 50 cents. At a 50 cent toll charge the aggregate increase in pollutant emissions is on the order of 1.1%.

5. In the example where the system operators set the toll on Keillor Road, it was found that the overall pollution levels on 114 Street increased by 18% and decreased by 80% on Keillor Road as the toll charge reached a maximum of $2 along Keillor Road. This increase in pollutant emissions is similar to the case when Keillor Road was closed where the pollution emissions on 114 Street were on the order of 20% for a UE assignment based on different objectives. Although, the 50 cent toll charge represented the equitable assignment in terms of the overall pollutant emissions on the network, the route flows on

114 Street and Keillor Road were significantly different and therefore ensuring equal pollutant emissions on both corridors was not possible. This was indicated by the fact that the total CO emissions on 114 Street ranged from 3.5 kg/h to 3 kg/h and the CO emissions on Keillor Road ranged from 1.5 kg/h to 0.4 kg/h as the toll increased.

6. It was also shown in the example that an optimal toll charge of 70 cents would generate maximum revenues from the users of Keillor Road. However, if the objective is to ensure that the total pollutant emissions are a minimum on the network, then the toll would have to be $0 on Keillor Road.

Chapter 7 - Conclusions and Recommendations

7.0 Overview

This thesis has implemented and analyzed several approaches to modelling traffic assignment with contemporary objectives. These objectives included minimizing fuel consumption, CO emissions, and HC emissions from a user equilibrium, system optimal and equity perspective. In Chapter 4, the concept of environmental objectives in a traffic assignment model was examined for a two link network and then analyzed on two larger networks -- the University network and the Ottawa network. Chapter 5 examined the potential for using the incremental traffic assignment technique to model traffic assignment problems with the objective of the people rather than the operators or users of the roadway. Furthermore, the concept of equity was examined with a simple two link network where non-conventional objectives and multiple user classes were implemented in the example problem. Finally, Chapter 5 concluded with an equity example on the University network where it was assumed that the people living adjacent to Keillor Road and 114 Street wanted to ensure that the pollution levels on both streets were the same. In Chapter 6, toll charges in traffic assignment modelling were examined. This chapter examined the potential for using traffic assignment techniques to model the effect of link flows and total travel time when the drivers' value of time was random. In summary, the thesis examined the possibility of including environmental objectives and equity principles in route guidance and electronic toll collection systems. This chapter is divided into two parts. Section 7.1 lists the major conclusions of the research and section 7.2 presents major recommendations for future research.

7.1 Conclusions

The major conclusions from the research presented in this thesis may be separated into three sections. The first section summarizes the conclusion developed from routing traffic based on environmental generalized cost functions. The second section lists the conclusions found when traffic is routed from an equity perspective. Finally, the third section presents the conclusions developed from modelling toll charges within the ASSIGN traffic assignment model.

7.1.1 Environmental Conditions in Traffic Assignment

1. It was found in a simple two link example that objectives that would seem to be complementary, for example, the reduction in travel time and the reduction in CO emissions, may actually conflict. It was found that CO emissions on the network are lower for a UE_TT assignment than a UE_CO assignment. It was also shown that link flows and pollutant emissions are similar for an "environmental" system optimal assignment and an assignment where drivers minimize their own travel time (i.e. UE_TT assignment).

2. The results of the analysis on the University network were divided into four sections: First the overall system costs were compared for the current 1993 demand level. Second, the route costs were analyzed. Third, the analysis was conducted at a microscopic level where individual link flows and pollutant emissions were examined when Keillor Road was open. Finally, the University network and Ottawa network were compared on the basis of a demand rate analysis. The next few findings and conclusions will be presented in this order.

a) It was found that for the present 1993 demand level on the University network, the largest pollutant emission difference based on different traffic assignment objectives was on the order of less than 1%. For example, the increase in travel time between a UE_TT and UE_CO assignment was approximately 0.4%. Similarly, the increase in system travel time was on the order of 0.74% when fuel consumption was minimized. The percentage increases in travel time on the network may seem small, however, it has been shown in previous literature (King and Mast, 1987) that ITS technologies for the purposes of reducing congestion improve a system by less than 7%. The small changes in system costs on the network when different traffic assignment objectives are implemented in the model, implied that using route guidance technologies or electronic tolls with the explicit objective of reducing air pollution is similar to applying ITS technologies to reduce congestion (i.e. travel time).

b) In the route analysis, it was found that the different traffic assignment objectives do have an effect on the overall route costs. For example, if the objective is a UE_CO assignment, the overall CO emissions would increase by 11% on 114 Street where the reference is a SO_CO assignment when Keillor Road is closed. In this example, CO emissions actually increase if the objective is a UE_CO assignment rather than a UE_TT assignment. It was also found that the pollutant emissions increase on 114 Street if drivers do not have access to Keillor Road. The increase in pollutant emissions and fuel consumption is on the order of 18% over all the objectives when a SO objective is implemented in the assignment program. Similarly, there is a 20% increase in pollutants on 114 Street for a UE assignment.

c) The impact of adding of removing Keillor Road on the University network causes some significant changes in individual link flows, travel time, and environmental conditions at certain locations along the 114 Street Corridor and Keillor Road. The analysis was done on a link basis to determine where the critical regions may occur if Keillor Road is closed. It was found that link flows increase on average by 600 v/h between 72 Ave. and 82 Ave. when Keillor Road is closed. The increase in link flow on 114 Street due to the closure of Keillor Road causes an increase in fuel consumption and pollutant emissions. The increase in CO emissions, for example was approximately 60 g/h. It was also found that there is on average a 2% increase in pollutant emissions and a 2.9% increase in overall travel time on the network when Keillor Road is closed.

d) It was found in the demand rate analysis that the highest change in total travel time on the University network is on the order of 1.2% for UE_F assignment which occurred in the middle demand level. It was also found that the CO emissions on the network increase by 0.35% for a UE_F assignment. This implied that using ITS technologies to route traffic to minimize pollution levels is the same as using ITS to route traffic to minimize congestion and thus link travel times on the network.

e) It was found that the total travel time for the Ottawa network increases to a peak of 12% at the high demand levels for a UE_CO assignment. It was also found that a UE_CO assignment results in higher CO emissions than if the drivers routed themselves to minimize their own travel time at high congestion levels. Similarly, if the objective is to ensure that the overall travel time on the network is a minimum, the total CO emissions actually increase to 3.5% at high demand levels where the minimum increase in CO emissions occurs in the middle demand levels. In essence, dual objectives of minimizing CO and link travel time may conflict. It was found from the demand rate analysis that both the University and Ottawa networks resulted in different trends because the University network is much smaller than the Ottawa network and therefore less routing options are available on the University network.

7.1.2 Modelling an Equitable Traffic Assignment

1. Traditional user equilibrium and system optimal traffic assignment techniques have been used to solve traffic assignment problems when the generalized cost functions are convex. However, the convex combinations algorithm (Frank-Wolfe algorithm) that is used to solve for a UE or SO assignment may no longer be adequate if different objectives such as the environment, equity and multiple user classes are applied to an assignment algorithm. The Frank-Wolfe algorithm that is used to solve for the global optimum in the user equilibrium assignment may need to be modified or discarded when non-convex functions, equity and multiple user classes are stipulated in the assignment problem.

2. It was found that incremental traffic assignment technique is adequate for modelling contemporary objectives and address the limitations of current traffic assignment models. These limitations include non-convex functions such as environmental cost functions, multiple user classes, and equity principles. The noise pollution example showed that the incremental assignment algorithm is capable of determining accurate link flows and aggregate statistics for equity objectives and multiple user classes when compared with an analytical solution.

3. The second two link example showed that if CO emissions are minimized from a UE, SO or SE point of view, the equitable assignment resulted in very similar link flows and overall CO emission levels as when the drivers are routed based on a UE_CO assignment. Therefore, charging the drivers for the amount of pollution they produce is similar to using route guidance systems to achieve equitable measures. It was also shown that a SE assignment resulted in an average increase in total travel time of 49% where the reference is a SO assignment for the same objective. This increase in travel time on the network is similar to a UE assignment.

4. For the University network, routing traffic with the objective of ensuring equal pollution levels on Keillor Road and 114 Street showed that the overall travel time on the network with respect to a SO assignment for the different objectives increased by an average of 1.9%. The overall fuel consumption and CO emissions increased on average by 1% and 0.95%, respectively. These increases in travel time and pollution levels are significant within ITS environments because it has been found that improvements to systems with ITS technologies is on the order of less than 7%. In effect, the example showed that implementing a route guidance system to achieve equitable measures at an aggregate level is similar to closing Keillor Road (another "equitable" measure) where it was found that the total pollutant emissions increase by 2% when Keillor Road is closed.

5. It was found that if a SE assignment is applied to ensure that 114 Street and Keillor Road have equal pollution levels resulted in higher pollution levels on Keillor Road and lower pollution levels on 114 Street. The increase in pollution levels on Keillor Road was on the order of 55% while the decrease in pollution on 114 Street was approximately 18%.

7.1.3 Modelling Toll Charges in Traffic Assignment

1. In Chapter 6, the ASSIGN model was used to integrate previous research on toll charges where the generalized cost function was dependent on the link travel, the user's value of time and a charge associated with the roadway. From the model results and

previous research for a simple network that represented the Braess paradox, it was found that the addition of a link may actually increase the total system costs (Braess Paradox). However by charging drivers that use the additional link, the model results showed a reversal of the Braess Paradox. The improvement to the overall system costs was between 1-3% depending on the demand level and whether the value of time was random or constant.

2. Furthermore, it was found through literature and from the model runs on the simple network that randomizing the users' value of time will result in higher link flows on the toll route than if the users' value of time was constant. For example, the link flows on the example network when the value of time was random never reached 0 v/h on the tolled roadway as the toll charge increased to a maximum of $3. In the thesis, the value to time was based solely on how people value their time where a lognormal distribution was used to represent the variation of the income distribution of the population.

3. The analysis of toll charges on the University network was based on the assumption that the residents adjacent to Keillor Road wanted the roadway closed for purposes of improving the environmental conditions but the users of the Keillor Road wanted the roadway to remain open in order for the drivers to improve their travel time or own generalized cost. In the example, the overall pollution levels on 114 Street increased by 18% and decreased by 80% on Keillor Road as the toll reached $2. The increase in pollutant emissions was directly related to the amount of vehicles diverted away from Keillor Road as the toll increased.

4. It was found that the overall pollution levels on the network are the same as those generated from a system equitable assignment when the toll was 50 cents. At a 50 cent toll charge the aggregate increase in pollutant emissions is on the order of 1.1%. Although, the 50 cent toll charge represented the equitable assignment in terms of the overall pollutant emissions on the network, the route flows on 114 Street and Keillor Road were significantly different that ensuring equal pollutant emissions on both corridors

was not possible. This was indicated by the fact that the total CO emissions on 114 Street ranged from 3 kg/h to 3.5 kg/h and the CO emissions on Keillor Road ranged from 1.5 kg/h to 0.4 kg/h as the toll increased.

5. It was also shown in the example that an optimal toll charge of 70 cents would generate maximum revenues from the users of Keillor Road. However, if the objective is to ensure that the total pollutant emissions are a minimum on the network, then the toll would have to be $0 on Keillor Road.

7.2 Recommendations

The studies in this thesis has raised a number of important questions that should be addressed if the environmental challenge is going to be efficiently implemented in ITS technologies. Several recommendations for further research are proposed.

1. Because the thesis dealt with different traffic assignment objectives and principles, detailed analyses towards appropriate generalized cost functions to model environmental conditions was not studied. Therefore, further research is required in determining cost functions that would better model driver behaviour towards the environment. A sensitivity analysis to determine appropriate generalized cost functions or factors to model environmental cost conditions for urban networks may be grounds towards further research.

2. The ASSIGN model should be calibrated and validated based on field data from the actual pollution levels obtained from the University network. This would ensure that the appropriate cost functions determined from a sensitivity analysis would be used in modelling vehicle emission levels.

3. It may be appropriate to include a generalized cost function that involves several objectives and not for example solely link travel time or CO production rate as was used

throughout the thesis. The function could include both travel time and environmental costs to represent the generalized cost function in the traffic assignment model.

4. The research was based on a static equilibrium model which generated aggregate link flows and cost data. However, it may be beneficial to examine vehicular emission controls with more dynamic models that consider acceleration/deceleration and idling vehicle modes, and multiple user classes. An assignment that considers the effect of congestion for different time periods may also need to be examined.

5. This research has examined traffic assignment when the demand rate is fixed. However, toll charges, environmental objectives and ITS technologies implies that drivers may decide not to make the trip or change their mode of travel. The traffic assignment model could be expanded to include variable demand rates and modal choice.

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APPENDIX A - ASSIGN User's Guide

A.1 Introduction

The ASSIGN model was developed to provide a means of performing both deterministic and/or stochastic traffic assignment on a highway or a street network given a set of link generalized cost relationships and estimated O-D demands rates. The ASSIGN model may also be used to route traffic such that the vehicular pollution levels on a network are minimized. For example, drivers' may wish to minimize their own pollution levels because they are charge a toll based on the amount of pollution they produce. Moreover, the system operators may also route traffic such that the total pollution levels on the network are a minimum or they may route traffic to ensure somekind of equitable assignment.

A number of North American's busiest traffic networks consists of a mixture of both freeway sections and traffic signal controlled surface streets. The objective of the assignment model is to analyze control strategies when a network is given an O-D demand. The ASSIGN model produces minimum path routes which in turn produces link flows or volumes based on a specified objective inputted by the user. Finally, link travel time information and pollutant emissions on the network based on the estimated link flows may be used to analyze the network for either long term or short term projects.

This manual provides a description of the input files used in ASSIGN. An example problem is used to show how the input data files are configured in ASSIGN to run the program. Furthermore, the results of the example problem are shown to indicate the capabilities of the ASSIGN model program.

A.2. Description of Main File

This section describes the structure and contents of the main file. The main file used in the ASSIGN model is called ASSIGN.FIL. This file identifies the key parameters required by the program such as, the input files, the output files and the directories where these data files are located. The ASSIGN.FIL file must be located in the same directory as the ASSIGN executable files. Each line of the ASSIGN.FIL file is described with specific reference to the ANET network example. Table A.1 shows the general syntax of ASSIGN.FIL using the ANET example.

Table A.1 - ASSIGN.FIL file

0	User/System/System Equitable Assignment
0 0.0	Algorithm-CC,MSA, Incremental, Stochastic Factor
5 3600 3600	No. of iterations, length of period, period duration
1 0 0 0 0 0 0 0	Generalized Cost Function
0	Incremental Assignment Indicator
anet\	Input file
anet\	Output File
anet1.dat	Node File
anet2.dat	Link file
anet3.dat	Signal file
anet4.dat	O-D demand file
none	Optional input tree file
anet.tre	Output tree file
anet.out	Output algorithm summary
none	Optional output file
none	Optional output file
none	Optional output file
none	Special output file used as a test file

The first line in ASSIGN.FIL indicates whether the program will route the drivers from a user equilibrium, system optimal or system equitable point of view. A value of zero indicates that the model will perform a user equilibrium assignment where the drivers route themselves to minimize their own generalized cost. A value of 1 indicates that the model will perform a system optimal assignment to minimize the total generalized cost on the network and a value of 2 is a system equitable type of assignment which is only used for research purposes.

The first parameter on the second line identifies what algorithm to use. A value of zero indicates that the program will use the convex combinations algorithm. It is therefore assumed that the vehicles have perfect knowledge of the link travel times and a macroscopic, deterministic, user equilibrium assignment will be performed. A value of one indicates that the program will use the method of successive averages (MSA) algorithm to determine link flows and travel times on the network. This latter algorithm will perform a deterministic or stochastic user equilibrium assignment depending on the value of the stochastic factor and depending on the generalized cost function listed in the next line. Finally, a value of 2 indicates the program will route traffic based on an incremental assignment where the link flows are updated either after every origin number or destination number.

The second parameter on line 2, value = 0.0, is referred to as the stochastic factor. A value of 0.0 ensures that the drivers have perfect knowledge of the link travel times and therefore a macroscopic, deterministic user equilibrium assignment will be performed using the MSA algorithm. A value greater than 0.0 indicates the perception error that drivers have with regards to the link travel times. Note that if the convex combinations algorithm option is invoked the value for the stochastic parameter is ignored. In the ASSIGN model it is assumed that when modelling the macroscopic, stochastic user equilibrium process the vehicles perceive the link travel times as a random variable that is normally distributed with a mean of t and a variance of kt. The stochastic parameter is simply the user specified coefficient of variation on a link that has an average travel time of 1 minute. Furthermore, for research purposes, the stochastic factor is also used as an indicator for modelling toll roads where a value of 0 would indicate that the generalized cost function associated with the toll road would be random and a value of 1 indicates that the cost associated with the roadway (i.e. driver's value of time) is constant.

The third line lists the number of iterations (5) the program uses to determine a solution. For large networks it is possible to achieve adequate results within 4 to 6 iterations (Sheffi, 1985) using the convex combinations algorithm and 10-15 iterations for the MSA algorithm.

The simulation time (3600 seconds) and the period duration (3600 seconds) are also listed on the third line. The simulation time identifies the length of time for OD's pairs to be loaded on the network and the period duration identifies the length of each assignment period. The number of assignment processes that will be performed by the ASSIGN model is equal to the simulation time divided by the period duration time.

The fourth line represents an identification code for the generalized cost function. There are 8 possible generalized cost function that may be used to determine the route flows based on minimizing different objectives. The first generalized cost function is the BPR function where the parameters of the function are identified in the link characteristics file. The environmental generalized cost functions are identified by the next 4 parameters listed in the following order: Fuel consumption, CO, HC, and NO emissions functions. The 5th generalized cost function is a modified travel time function developed by Spiess (1990). The final two cost functions are used for toll roads where the BPR function and the modified travel time function are subject to a cost associated with a roadway and a driver's value of time.

The fifth line is an indicator used in the incremental traffic assignment model. The incremental assignment in ASSIGN identifies the minimum path routes starting at each origin and therefore, if the indicator is zero, the generalized cost function will be updated only for each new origin. A value of 1 indicates that the generalized cost function is updated after each destination where new minimum path routes are found for each origin-destination pair. If the indicator is 1, the executable time within the program is much longer.

The sixth and seventh line in the ASSIGN.FIL file are the subdirectories which indicate the location of the input and output files, respectively (i.e. ANET\).

Lines eight through eleven list the input files that are located in the input subdirectory. These files must be placed in the order specified where ANET1.DAT lists the nodes and their locations, ANET2.DAT lists link information such as link length, number of lanes, free flow speed, etc., ANET3.DAT specifies the signal timing plan for each link in the network, and ANET4.DAT describes O-D traffic demand. The input files utilized in INTEGRATION (Van Aerde, 1992) can be used directly in the assignment program without making any changes to the files. The fifth input file (line eleven), is only used for research purposes on the University network and is therefore not explained in this section.

There are two major output files listed in the main file and these are indicated on lines twelve and thirteen. In the example, output files are listed as ANET.TRE, ANET.OUT. ANET.TRE lists the trees used to arrive at the final solution. ANET.OUT summarizes link flow information and algorithm convergence results. The subsequent lines in the ASSIGN.FIL file are research purpose files and "none" or "NONE" is entered to indicate that these file are not required.

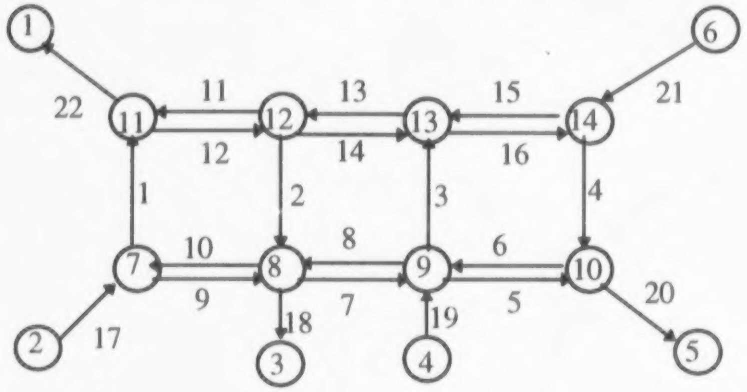

Figure A.1 - ANET Network

A.3 Overview of ANET Test Network

A test network called ANET, shown in Figure A.1, was developed to demonstrate the execution of the model and to illustrate some of its features. This network consists of 4 origin/destination zones , 10 additional nodes and 22 one-way links. A high speed signalize arterial runs between nodes 11-14. A parallel arterial is also available for travel across the network and is shown between nodes 7 -10. In addition, various connectors permit diversion between the freeway and the arterial at a number of selected places. The model does not require links to be labeled by type, such as freeway, arterial of ramp. Instead, these differences between links are specified by the user in terms of providing unique link traffic flow characteristics, such as saturation flow rate, number of lanes, free speed, and shape of travel time relationship.

A.4 Executing the model

The ASSIGN module has been set up to run on any 386 or 486 microcomputer with a least 2Mb of memory and a math co-processor. The ASSIGN model is presently not available commercially and is used for internal research.

There are three steps required to run the program.

The first step is to create the ASSIGN.FIL file, the four input files, the subdirectories and copy the required input files into the input subdirectories.

The second step is to ensure that parameters from the input files such as the number of links does not exceed the constraints of the program which are found in the ERR.OUT file.

The final step is to place the disk in the current drive (or xcopy all the files from the disk onto the hard drive and enter the following command at the DOS prompt in the directory where the ASSIGN.EXE and other necessary executables files are located:

```
ASSIGN <<RETURN>>
```

The ASSIGN program will then perform a traffic assignment routing based on the parameters specified in the main file, ASSIGN.FIL. To execute the model for other conditions, for example, system equilibrium assignment, it is necessary to modify the ASSIGN.FIL or modify the sample input files.

A.4.1 Executing Multiple ASSIGN Runs Unattended

In order to carry out multiple model runs that may be associated with some sensitivity analyses, it is possible to set up a DOS batch file which automatically executes the ASSIGN model a number of times unattended, each time with a different input data set. It is necessary, however, that for each model run the final results be sent to a new set of output files otherwise the contents of earlier runs will be overwritten.

An example of this type of batch processing is shown in Table A.2. It is shown that the ASSIGN model will be executed twice. The first run will be executed with the original input data files but with a modified main file. The second run will be executed with a modified main file and input file. The output generated for both runs will be saved under new names.

Table A.2 - Batch Processing

```
rem - Starting Batch Processing of 2 different ASSIGN model runs
copy ANET.FIL ASSIGN.FIL
CALL ASSIGN
copy ANET\ANET.OUT ANET\ANET1.OUT
rem
copy ANET\ANET2a.DAT ANET\ANET2.DAT
CALL ASSIGN
copy ANET\ANET.OUT ANET\ANET2.OUT
rem - All ASSIGN runs are complete
```

A.5 Description of Model Inputs

The ASSIGN program requires 4 mandatory types of input data. The contents of these files are discussed in this section. The mandatory input files are:

1. ANET1.DAT: Node coordinates for graphic purposes and node type designation
2. ANET2.DAT: Link characteristic data file
3. ANET3.DAT: Signal timing file (cycle length, green times, and offsets)
4. ANET4.DAT: Vehicle demand file (departure time, origin and destination demand)

A.5.1. ANET1.DAT

The ANET1.DAT as shown in Table A.3 lists primarily the X and Y coordinates of all zones and nodes in the network. The first line in the file is the file header. Line 2 indicates the total number of nodes. Subsequent lines within the file provides for each node its number, the X and Y coordinate which are specified in km, the node type, and information about changeable message signs which is not yet used in ASSIGN.

The X coordinates should increase from West to East whereas the Y coordinates should increase from South to North. The coordinates are used for display purposes only and have no effect on the link lengths identified by the user in the link file -- ANET2.DAT.

There are four possible node types (field 4) within ASSIGN. Node type 1 are nodes that are both trip origin and destination zone centroids. Node type 2 is a destination zone centroid only. Node type 3 is an origin only node and node type 4 is used when the node is neither an origin or destination zone centroid and is therefore an intermediate point along the vehicle's trip path.

Table A.3 - Node File

```
ANET Node File
14
1    1    4    1    0
2    1    1    1    0
3    3    1    4    0
4    4    1    4    0
5    6    1    1    0
6    6    4    1    0
7    2    2    4    0
8    3    2    4    0
9    4    2    4    0
10   5    2    4    0
11   2    3    4    0
12   3    3    4    0
13   4    3    4    0
14   5    3    4    0
```

Line 1:	Title
Line 2:	Number of nodes in the network
Subsequent Lines	
Nodenum	Node number identifier
x:	x-coordinate of the node location (km)
y:	y-coordinate of the node location (km)
NZ:	Node/Zone identifier 1 = Both trip origin and destination 2 = Trip destination only 3 = Trip origin only 4 = node only
Addtional information - not used in ASSIGN	

Details of the ANET1.DAT File

The ANET1.DAT file shows that there are 4 O-D pairs. The remaining nodes are connectors within the network. It should also be noted that the node numbers are in sequential order. However, it is not necessary to number the nodes successively. For example, node number 14 could have been codes as node number 20.

A.5.2. ANET2.DAT

ANET2.DAT is a link descriptor file which is shown in Table A.4. The first line is the file header. Line 2 list the number of links in the network. Subsequent lines lists for each link, the start and end node, link lengths, free speed, platoon dispersion factor, travel time relationship parameters, and saturation flow rate per lane. These parameters control the traffic flow characteristics of a link. In addition, the link files lists, the number of lanes, traffic signal control, HOV indicator, a surveillance level code, toll charge on the link, and a qualitative descriptor or name of the link. A description of the features in the ANET2.DAT file may be found in the following sections.

Link Flow Characteristics

Link capacity is calculated indirectly within the model. Equation A.1 describes the link capacity in terms of the number of lanes and saturation flow rate per lane inputted directly by the user. The link capacity is an initial gross value which is reduced internally within the program when a signal is provided at an intersection.

$$\text{Link Capacity} = \text{Saturation flow} * \text{Number of lanes} \qquad \text{A.1}$$

Link travel time functions at a link can vary depending on the parameters the user indicates at fields 9 and 10. One of the travel time relationships commonly used is the function developed by the Bureau of Public roads which is shown in Equation A.2. The BPR function may be initiated by coding a value of 1 in the first column of line four in the ASSIGN.FIL file.

$$tt_a = ttf_a(1+\alpha_a(\frac{V_a}{c_a})^{\beta_a}) \qquad \text{A.2}$$

Where:

tt_a = Travel time on link a

ttf_a = Free flow link travel time

V_a = Volume on link a

c_a = Capacity of Link a

α_a,β_a = BPR constants

Furthermore, it is also possible to use a second travel time function to determine route flows within the network. This function corresponds to the relationship developed by Spiess (1990) and it is shown in Equation A.3. The parameters in fields 9 and 10 correspond to the α and γ of Equation A.3, and may vary depending on the values inputted by the user.

$$tt_a = T_a\left(1+\gamma_a+\sqrt{\beta_a^{\,2}+\alpha_a^{\,2}\left(1-\frac{x_a}{N_a}\right)^2}-\alpha_a\left(1-\frac{x_a}{N_a}\right)-\beta_a\right) \qquad \text{A.3}$$

$$\beta_a = \frac{\gamma_a\left(\alpha_a-\frac{\gamma_a}{2}\right)}{\alpha_a-\gamma_a}$$

Where:

T_a = Free flow link travel time
γ_a, α_a, β_a = Congestion parameters
x_a = Volume on link a
N_a = Capacity of link a

In essence, the α and β parameters in the BPR function or the α and γ parameters for the second travel time relationship permits the user to specify different speed-flow relationships. For example, values of $\alpha = 0.15$ and $\beta = 4$ inputted into the BPR function corresponds to the parabolic speed-flow relationship that is used in the U.S. Highway Capacity Manual.

It should also be noted that it is not required to route traffic based solely on minimizing link travel times. Additional cost functions have also been provided in the ASSIGN program to route traffic such that environmental costs are minimized. These cost functions were shown in Chapter 2 where the ASSIGN program adopted the TRANSYT -7F average speed fuel consumption and pollutant emissions functions to determine the amount of pollutants produced by the drivers on the network. The parameters in fields 9 and 10 are still needed in the program because link travel times on the network are compared even when traffic is routed on the basis of other objectives.

Table A.4 - Link Characteristics File

```
ANET Link File
22
1    7   11  1.0  60  2000  2  0  0.15  4      1  1  0  0  1  0  north
2   12    8  1.0  60  2000  2  0  0.15  4  10002  0  0  0  1  0  south
3    9   13  1.0  60  2000  2  0  0.15  4      2  1  0  0  1  0  north
4   14   10  1.0  60  2000  2  0  0.15  4  10002  0  0  0  1  0  south
5    9   10  2.0  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
6   10    9  2.0  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
7    8    9  2.0  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
8    9    8  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
9    7    8  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
10   8    7  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  arterial
11  11   12  1.5  80  2000  2  0  0.15  4      1  2  0  0  1  0  freeway
12  12   11  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  freeway
13  13   12  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  freeway
14  12   13  1.5  80  2000  2  0  0.15  4      2  2  0  0  1  0  freeway
15  14   13  1.5  80  2000  2  0  0.15  4      2  1  0  0  1  0  freeway
16  13   14  1.5  80  2000  2  0  0.15  4      0  0  0  0  1  0  freeway
17   2    7  1.5  -1  2000  2  0  0.15  4      0  0  0  0  1  0  dummy
18   8    3  1.5  60  2000  2  0  0.15  4      0  0  0  0  1  0  south
19   4    9  1.5  60  2000  2  0  0.15  4  10002  0  0  0  1  0  north
20  10    5  1.5  -1  2000  2  0  0.15  4      0  0  0  0  1  0  dummy
21   6   14  1.5  -1  2000  2  0  0.15  4      0  0  0  0  1  0  dummy
22  11    1  1.5  -1  2000  2  0  0.15  4      0  0  0  0  1  0  dummy
```

Line 1: File Title
Line 2: Number of links in the file (integer)

Subsequent Lines

Link Number: Number of the link
Start Node: Node which represents start of link
End Node: Node which represents end of link
Length: Link Length (km)
Free speed: Free flow speed of link (km/h)
Num. Lanes: Number of lanes on a link (integer)
Platoon: Not used in ASSIGN (input a value of 0)
A: α parameter for the BPR function
B: β parameter for the BPR function
Signal Number: Number of the traffic signal which controls the link (integer)
Phase 1: Number of the phase for the above signal
Phase 2: Number of the second phase for the above signal
HOV indicator: Not used in ASSIGN
Surveillance: 1 = gen. cost dependent on flow; 2 = gen. cost independent of flow
Cost: Toll Charge on link
Link Name: Description of link

Traffic Signals

Traffic signals are specified for each link in field 11 of the ANET2.DAT file. Field 11 indicates the traffic signal number and field 12 and 13 indicate the phases at which the signal is active. The traffic signal number is used as a reference to the timing plans in the signal control file

A non-signalized link is coded by indicating a value to zero to field 11. Yield signs are coded as traffic signal 10001 and stop signs are coded as traffic signal 10002. The program recognizes the code associated with a stop or yield sign and assigns a constant travel time penalty of 10 seconds at the yield sign and 20 seconds at the stop sign. At this stage in the program, additional turning movement penalties are not assigned and explicit gap-acceptance behaviour is not modelled.

It should be noted that traffic signals are not modelled at a given node. Instead, they are coded as controlling the discharge privileges of the links that meet at a node. A complex intersection configuration as shown in Chapter 3, Figure 3.4 may be used to model explicit turning movements and intersections at great detail. The decision to model this type of intersection is dependent on the level of detail required by the user.

The HOV (High Occupancy Vehicle) indicator in field 14 is not used in ASSIGN. This value should be set to zero for consistency. The surveillance factor (field 15) is used to indicate whether travel time is dependent on traffic flow or whether travel time remains constant with changes in flow. A value of zero indicates that the travel time on a link remains constant whereas a value of one indicates that travel time on the link varies with flow.

Field 16 is the cost associated with the link. The cost on the link may be referred to a portion of the total toll charge along a corridor. The toll on the roadway is dependent of the user specified charge and the driver's value of time which is proportional to an average income distribution of 10$/hour.

Dummy Links

Zone connectors are used to connect the network with the origin and destination zones. A dummy link is a term often used in modelling which indicates that the link has no important meaning within the network. In ASSIGN, a dummy link is designated when the free flow speed is set to -1 km/h. The program will assign a travel time penalty to the dummy link during any tree/route building. Consequently, only traffic originating from or destined for the given zone will have no other alternative links and will use these links and other traffic will be discouraged from shortcutting due to the large travel time penalty.

If a link is assigned a free flow speed of -1 km/h, ASSIGN will automatically set all other link characteristics to the dummy link defaults regardless of what is specified in other fields. For example, if the saturation flow is specified as 2000 v/h for a dummy link, the ASSIGN program will change this saturation flow to 4000 v/h.

Details of the ANET2.DAT File

The ANET2.DAT file shows the possible features of the link characteristics file. It is shown in Table A.4 that the network consists of 22 links of which two are signalized links and 3 are stop controlled. There are four dummy links that connect the zones to the network. Furthermore, it is indicated that all links have the same saturation flows of 2000 v/h/lane where two lanes have been specified for each link. There are two distinct free flow travel speeds on the network: 80 km/h and 60 km/h which represents a network that consists of both freeways and arterial routes. The travel time relationship is represented by the BPR function where the parameters are $\alpha = 0.15$ and $\beta = 4$.

A.5.3. ANET3.DAT

ANET3.DAT is a signal descriptor file and is illustrated in Table A.5. The first line is the file header. Line 2 permits the user to indicate the number of signals within the network. Column 2 of this line also lists the number of different fixed-time signal plans and the duration for each plan. Subsequent lines list for each signal number, the duration of the cycle length, offset of the start of phase 1, the number of phases, the durations of the green intervals for each phase and the lost times associated with each phase. The last column lists the optimizer interval which is presently not used in ASSIGN.

Table A.5 - Signal Control File

```
ANET Signal Control File
2      2      1800
1
1  60   30   70   0   2   41   4   11   4   0
2  60   30   70   0   2   41   4   11   4   0
2
1  80   30   70   0   2   51   4   21   4   0
2  80   30   70   0   2   51   4   21   4   0
```

Line 1:	File Description
Line 2	
Numsig:	Number of traffic signals
Numplan:	Number of signal traffic plans
Plan Dur:	Signal plan duration is seconds
Subsequent Lines	
Signal Number:	Number of the signal
Initial Cycle:	Initial cycle time (seconds)
Min. Cycle:	Not used in ASSIGN
Max Cycle:	Not used in ASSIGN
Offset:	Not used in ASSIGN
Num. Phases:	Number of phases at the signal
green:	Effective green time of phases (seconds)
Lost time:	Effective lost time of phase (seconds)
Optimizer:	Not used in ASSIGN

Details of the ANET3.DAT File

The ANET3.DAT file indicates that there are 2 set of signal timing plans within the hour. The first plan has a cycle length of 60 seconds where the green time is 41 seconds for phase 1 and 11 seconds for phase 2 with a loss time of 4 seconds for each phase. In the second phase, the cycle length is 80 seconds where the green times are 51 and 21 seconds for phases 1 and 2, respectively.

A.5.4. ANET4.DAT

ANET4.DAT is the origin-destination file. This file is shown in Table A.6. Line 1 is similar to the other input files where a file header is inputted by the user. Line 2 indicates the total number of origin-destination pairs considered within the network. Subsequent lines list for each origin-destination number, the departure rate, the fraction of the vehicle headway that is random (Note: this is not used in ASSIGN), and the time at which the given O-D flow rate begins and ends. Columns 8 through 12 indicate the fraction of vehicles that are of a specific type. Vehicle types are exclusive to the INTEGRATION model and they are not used in ASSIGN.

Table A.6 - Demand File

```
ANET Demand File
5
1  2  1  1000  0     0  3600  1  0  0  0  0
2  2  5  2000  0     0  3600  1  0  0  0  0
3  6  1  2000  0     0  3600  1  0  0  0  0
4  6  5  1000  0     0  1800  1  0  0  0  0
5  6  5   500  0  1800  3600  1  0  0  0  0
```

Line 1:	File Description
Line 2:	Number of origin-destination pairs
Subsequent lines	
Cell number:	O-D number
Origin:	Origin node for given O-D number
Destination:	Destination node for given O-D number
Odrate:	Departure rate for given O-D number
Krand:	Not used in ASSIGN
Starttime:	Time at which O-D flow rate starts (seconds)
Endtime:	Time at which O-D flow rate ends (seconds)
vehicle types:	Not Used in ASSIGN

It should be noted that several O-D rates can be specified for the same O-D pair using separate time periods. Furthermore, and O-D pair is of 0.0 is permitted but it does not result in an addition of vehicles on the network. In the example presented above, it is shown that the demand for the O-D pair number 6 - 5 increases by 500 v/h in the last half hour of the simulation time.

Details of the ANET4.DAT File

Table A.6 illustrate that there are five O-D demand rates on the network. The first four O-D pairs start at time zero and end at time 3600 seconds. The last demand rate begins and ends at the same zones as in the previous demand level but the start time has been specified at 1800 seconds within the simulation time.

A.6 Illustration of Typical Model Outputs

The model provides 4 types of outputs for interpretation by the model user:

a. On-Screen
b. Run Error File (ERR.OUT)
c. Aggregate Travel Time Output (ANET.OUT)
d. Tree Output File (ANET.TRE)

These output files are briefly discussed below using the results produced from the ANET network example. It should be noted that the Main file lists other output file types. However, these output files are presently only used for special research purposes in ASSIGN.

a. On-Screen Text (Displayed on Video Monitor)

While the program is running, errors are detected and stated after each input file is read. If any errors should occur, the program is terminated and the user is told to view the ERR.OUT file. If there are no present errors in the data entry the program will then display the network layout, the total travel time, and the objective function on the screen for each iteration.

b. Simulation Run Error File (ERR.OUT)

The ERR.OUT file is automatically created in the current directory when the program is initiated and serves two main functions. In the first instance, the ERR.OUT file provides a listing of the network size constraints that have been built into a particular version of the program. Items listed, for example, are the maximum node number, the maximum link number, etc. This list assists the user in determining the source and nature of the error as well as indicating the size of the network that can be modeled.

In the second instance, the file provides a listing of any errors detected during the course of running the program. The error statements refer to problems with input data processing. For example, error 1040 states that a certain input file cannot be found. The error descriptions, while brief, provide an adequate guide to assist in correcting the error.

c. Aggregate Output Statistics (ANET.OUT)

The initial output in file ANET.OUT of the ASSIGN module provides an echo of the data input into the model. The echo indicates whether or not the data files were read successfully. In addition, ANET.OUT summarizes the link and algorithm convergence results. The link summary includes traffic flow, free flow travel time and the estimated travel time for each link. Furthermore, the ANET.OUT files lists the link fuel consumption, CO, HC and NO emissions. Table A.7 shows the link flow and algorithm summary results for the ANET network where the objective is to ensure that the drivers minimize their own travel times. It should be noted that the link fuel consumption and pollutant emission results are only shown for the first four links on the network and only the final aggregate results are shown in order to minimize the memory required in the output file.

The algorithm summary shows the iteration number, the corresponding lambda value, the weight given to the AON route, the value of the objective function, and the total system travel time. The purpose of each iteration is to minimize the objective function. As shown in the ANET.OUT file, the objective function decreases for each iteration in this example because the static/deterministic case was chosen. It is also shown in the algorithm summary that after two iterations, the program has converged where the total user equilibrium travel time on the network is 489.224 veh-hours.

d. Tree Output File (ANET.TRE)

The ANET.TRE file produces a listing of the minimum path trees. The format is similar to the input file ANET9.DAT in the INTEGRATION manual where for any node, the next link a vehicle should take in order to reach the desired destination is identified. The ANET.TRE file is illustrated in Table A.8. The first line of the ANET.TRE file is a title describing the output file. Line 2 lists the number of the first minimum path route and its corresponding weight. It is shown in Table A.8 that the first set of trees has a weight of 0.5317 and the second set of trees has a weight of 0.4628. Subsequent lines lists for each node the next link that the vehicle should take. It should be noted that columns 4 and 5 represent non-destinating nodes (node numbers 3 and 4) and therefore the link numbers are zero. Similarly, columns two and six do not have link numbers because links emanating from these nodes are one directional links heading away from the destination.

Table A.7 - ANET.OUT

```
   File  1 is anet1.dat
   File  2 is anet2.dat
   File  3 is anet3.dat
   File  4 is anet4.dat
   File  5 is none
   File  6 is anet.tre
   File  7 is anet.out
   File  8 is none
   File  9 is none

Successfully read main batch file
Successfully read file: anet1.dat
Successfully read file: anet2.dat
Successfully read file: anet3.dat
Successfully read file: anet4.dat
Successfully read file: none

*****************************************************************************

 ***** Link Results for Period           1

 Number of iterations =          10
*****************************************************************************
 Travel Time Results for Assignment
 ============================================================================
 link      cap     volume     free flow  estimated  marginal        total
                            —travel time———travel time—
          (vph)    (vph)                     (seconds)
 ============================================================================
    1    2641.67   1924.36    60.0000   103.7078   147.4155     199570.67
    2    4000.00      0.00    60.0000    80.0000    80.0000          0.00
    3    2641.67      0.00    60.0000    60.0000    60.0000          0.00
    4    4000.00   1174.36    60.0000    97.6153   115.2307     114635.16
    5    4000.00   2000.00    90.0000   135.0000   180.0000     270000.00
    6    4000.00    924.36    90.0000   110.7980   131.5960     102416.84
    7    4000.00   2000.00    90.0000   135.0000   180.0000     270000.00
    8    4000.00    924.36    90.0000   110.7980   131.5960     102416.84
    9    4000.00   2000.00    90.0000   135.0000   180.0000     270000.00
   10    4000.00    924.36    90.0000   110.7980   131.5960     102416.84
   11     891.67      0.00   112.5000   112.5000   112.5000          0.00
   12    4000.00   1075.64   112.5000   142.7525   173.0050     153550.86
   13    4000.00   1075.64   112.5000   142.7525   173.0050     153550.86
   14     891.67      0.00   112.5000   112.5000   112.5000          0.00
   15     891.67   1075.64   112.5000   248.2121   383.9242     266987.88
   16    4000.00      0.00   112.5000   112.5000   112.5000          0.00
   17    4000.00   3000.00     7.2000    12.6000    18.0000      37800.00
   18    4000.00      0.00    60.0000    60.0000    60.0000          0.00
   19    4000.00      0.00    60.0000    80.0000    80.0000          0.00
   20    4000.00   2250.00     7.2000    11.2500    15.3000      25312.50
   21    4000.00   2250.00     7.2000    11.2500    15.3000      25312.50
   22    4000.00   3000.00     7.2000    12.6000    18.0000      37800.00
 _____________________________________________
                                        Total  ==>     592.159      hrs
                                        UESTAT ==>     489.224      hrs
```

```
Travel Time Results for Assignment - BPR + Vot
==============================================================================
link       cap      volume      free flow  estimated  marginal        total
                             ——travel time————travel time——
           (vph)    (vph)                   (seconds)
==============================================================================
   1      2641.67   1924.36     60.0000   103.7078   147.4155       199570.67
   2      4000.00      0.00     60.0000    80.0000    80.0000            0.00
   3      2641.67      0.00     60.0000    60.0000    60.0000            0.00
   4      4000.00   1174.36     60.0000    97.6153   115.2307       114635.16
 ______________________________________

                                            Total   ==>    592.159 hrs
                                            UESTAT  ==>    489.224   hrs


Fuel Consumption Results for Assignment
==============================================================================
link       cap      volume                 estimated  marginal          total
                                                ——     rate   —
            vph)     (vph)                   (gallons)
==============================================================================
   1      2641.67   1924.36                  0.0251     0.0301          48.30
   2      4000.00      0.00                  0.0227     0.0227           0.00
   3      2641.67      0.00                  0.0214     0.0214           0.00
   4      4000.00   1174.36                  0.0244     0.0263          28.68
 _______________________________________

                                              Total ==>      664.931      gal
                                              UEfuel==>      647.032      gal


CO Emission Results for Assignment
==============================================================================
link       cap      volume                 estimated  marginal         total
                                                ——      rate    —
            vph)     (vph)                        (gms)
==============================================================================
   1      2641.67   1924.36                  0.5583     0.6852        1074.38
   2      4000.00      0.00                  0.4937     0.4937           0.00
   3      2641.67      0.00                  0.4518     0.4518           0.00
   4      4000.00   1174.36                  0.5408     0.5907         635.13
 _______________________________________

                                              Total ==>     14.2772      kgs
                                              UECO ==>      13.5928      kgs


HC Emission Results for Assignment
==============================================================================
link       cap      volume                 estimated     marginal       total
                                               ——     rate    —
            vph)     (vph)                        (gms)
==============================================================================
   1      2641.67   1924.36                  0.0465     0.0568          89.49
   2      4000.00      0.00                  0.0413     0.0413           0.00
   3      2641.67      0.00                  0.0381     0.0381           0.00
   4      4000.00   1174.36                  0.0451     0.0491          52.95
 _______________________________________

                                              Total ==>        1.19862  kgs
                                              UEHC  ==>        1.1468    kgs
```

```
NO Emission Results for Assignment
 ===========================================================================
 link       cap      volume                      estimated    marginal       total
                                                    ---        rate    --
            vph)     (vph)                                   (gms)
 ===========================================================================
    1     2641.67   1924.36                        0.0591     0.0519        113.79
    2     4000.00      0.00                        0.0668     0.0668          0.00
    3     2641.67      0.00                        0.0875     0.0875          0.00
    4     4000.00   1174.36                        0.0603     0.0563         70.84
 _____________________________________
                                              Total ==>        2.36836     kgs
                                              UENO  ==>        2.92438     kgs


 **************************************************

USER EQUILIBRIUM ASSIGNMENT

CONVEX COMBINATIONS ALGORITHM

LINK COSTS ARE BASED ON  TT
 **************************************************

Period          1
**** Algorithm Summary ****

Iteration  lambda    Weight  UE Objective SO Objective
                              veh-hours    veh-hours
=====================================================
       1   1.0000    0.5378    528.493      679.041
       2   0.4622    0.4622    489.224      592.159
       3   0.0000    0.0000    489.224      592.159
       4   0.0000    0.0000    489.224      592.159
       5   0.0000    0.0000    489.224      592.159
       6   0.0000    0.0000    489.224      592.159
       7   0.0000    0.0000    489.224      592.159
       8   0.0000    0.0000    489.224      592.159
       9   0.0000    0.0000    489.224      592.159
      10   0.0000    0.0000    489.224      592.159
```

Table A.8 - ANET.TRE

```
Tree output from Assignment program
          1 0.53782
    1     0      0      0      0      0      0
    2    17      0      0      0     17      0
    3     0      0      0      0      0      0
    4    19      0      0      0     19      0
    5     0      0      0      0      0      0
    6    21      0      0      0     21      0
    7     1      0      0      0      9      0
    8    10      0      0      0      7      0
    9     8      0      0      0      5      0
   10     6      0      0      0     20      0
   11    22      0      0      0     11      0
   12    12      0      0      0      2      0
   13    13      0      0      0     16      0
   14    15      0      0      0      4      0
          2 0.46218
    1     0      0      0      0      0      0
    2    17      0      0      0     17      0
    3     0      0      0      0      0      0
    4    19      0      0      0     19      0
    5     0      0      0      0      0      0
    6    21      0      0      0     21      0
    7     1      0      0      0      9      0
    8    10      0      0      0      7      0
    9     8      0      0      0      5      0
   10     6      0      0      0     20      0
   11    22      0      0      0     11      0
   12    12      0      0      0     14      0
   13    13      0      0      0     16      0
   14     4      0      0      0      4      0
```